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MONTHLY WEATHER REVIEW

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MONTHLY WEATHER REVIEW

First published in 1872, the Monthly Weather Review serves as a medium of publication for technical contributions in the field of meteorology, principally in the branches of synoptic and applied meteorology. In addition each issue contains an article descriptive of the atmospheric circulation during the month over the Northern Hemisphere with particular reference to the effect on weather in the United States. A second article deals with some noteworthy feature of the month's weather. Illustrated. Annual subscription Domestic, $3.50; Foreign, $4.50. Subscription to the *Review* does not include the *Supplements* which have been issued irregularly and are for sale separately.

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(Continued on inside back cover)

The Weather Bureau desires that the *Monthly Weather Review* serve as a medium of publication for original contributions within its field, but the publication of a contribution is not to be construed as official approval of the views expressed.

The issue for each month is published as promptly as monthly data can be assembled for preparation of the review of the weather of the month. In order to maintain the schedule with the Public Printer, no proofs will be sent to authors outside of Washington, D. C. Requests for a limited number of reprints of the more important contributions can be granted; such requests should be made by the author on the first page of his manuscript.

The printing of this publication has been approved by the Director of the Bureau of the Budget, February 11, 1952

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A STUDY OF HURRICANE TRACKS FOR FORECASTING PURPOSES[1]

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[Manuscript received March 2, 1953]

INTRODUCTION

The prediction of the motion of tropical cyclones continues to be one of the major problems of forecasting in tropical and subtropical latitudes. One main difficulty lies in the fact that many of the techniques and aids suggested through the years require more extensive data than ordinarily are available to the forecaster. Two simple approaches which do not depend on a great amount of synoptic information are those based on climatology and persistence. These are the primary concern of this paper. Under the former approach, insight into the motion of the storm is given by the behavior of past storms in the same region and in the same month. In the latter, prediction is based on the behavior of the same storm during its previous history; usually, the preceding 24-hour period is considered.

Although their reliability is at times questioned, these approaches are used frequently at forecasting centers. Many times they are the only available tool in oceanic regions where data are inadequate for a confident analysis of the tropospheric flow in the area of the storm. Even when a reliable upper-air analysis is available, a careful study of the previous history of the storm should precede any forecast. The previous track gives the best indication of what the steering current has been and, thus, will help in deducing the future one.

Since, for some time to come, hurricane forecasters will have to deal with inadequate data, we should attempt to extract from past experience everything which leads toward a more efficient and confident application of the statistics. The present study represents such an attempt. The climatological data on hurricane tracks are reduced to a form which permits a quantitative estimate of the probability of success of persistence forecasting.

[1] This is a report on research conducted under contracts between the Office of Naval Research and the University of Chicago.

DATA AND METHOD OF ANALYSIS

The data used consist of tracks of tropical cyclones of all intensities charted in the Caribbean Sea, the Gulf of Mexico, and adjacent regions of the Atlantic Ocean during the period 1887–1950. In these 64 years, 473 storms were observed. Cyclone tracks for the period 1887–1932 are given in Mitchell's publications [1, 2]. After 1932, the tracks appear in annual summaries of the *Monthly Weather Review*.

The region from 10° N. to 35° N. and from 40° W. to 100° W. was divided into 5° latitude-longitude squares for the computations. In each square, a spot approximately in the center of each storm path was taken as the observation point, and the direction and speed of motion in the preceding and following 24-hour periods were tabulated. Each storm supplied one observation regardless of the time it took to move through the square. The numbers in the inner circles in figure 5 indicate the number of storms observed in each square during each month of the hurricane season, June through November, for the entire 64 years.

FREQUENCY OF STORMS

Table 1 gives the average monthly frequency of storms on a 10-year basis.

ANNUAL FREQUENCIES

The average annual frequency per 10 years is 74. About 80 percent of this total occurs during the three-month period August to October. The frequency in

TABLE 1.—*Average monthly frequency of tropical cyclones of all intensities during the period 1887–1950, reduced to 10-year basis*

	May	June	July	Aug.	Sept.	Oct.	Nov.	Total
Frequency	1	4	5	16	24	19	4	74
Percentage frequency	1	6	7	22	32	26	6	100

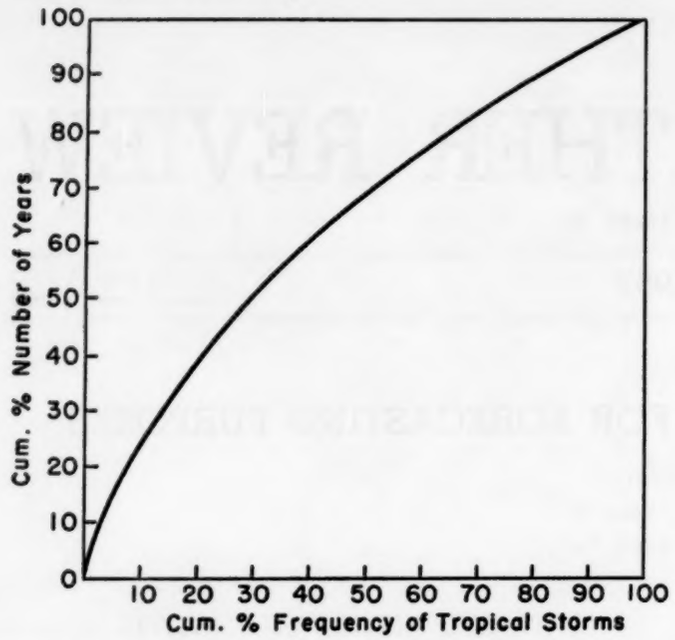


FIGURE 1.—Cumulative percent frequency distribution of the number of tropical storms against cumulative percent of years studied.

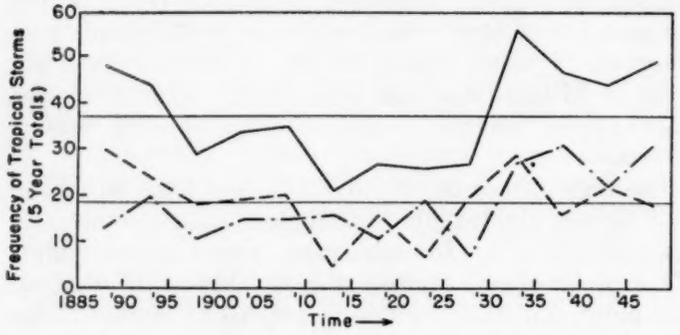


FIGURE 2.—Frequency of tropical cyclones of all intensities in the Caribbean-Atlantic area by five-year sums from 1886-1950. Solid curve indicates total frequency; dashed curve, frequency of storms formed east of 70° W.; dot-dashed curve, storms formed west of 70° W. Thin horizontal solid lines indicate the averages on a five-year basis.

individual years varied from a minimum of 1 recorded in 1890 to a maximum of 21 in 1933. Low frequencies of two storms per season have been observed several times, most recently in 1929 and 1930. This constitutes an extreme low of activity during a two-year period. On account of the variability of storm frequency, seasons with storm totals below the mean occur more often than active seasons. This is illustrated in figure 1, which shows that 70 percent of the total number of seasons account for only 50 percent of the total number of storms, and that 50 percent of the storms occurred in only 30 percent of the seasons. Also, 40 percent of the seasons account for only 20 percent of the total frequency of storms.

A graph of seasonal frequency against time shows great variability from one season to the next. The product-moment correlation coefficient for a one-year lag is only 0.19. However, a graph of successive five-year totals reveals a very interesting feature (fig. 2). The correlation coefficient for successive five-year totals is 0.46, a relatively high value. Above average values were observed during the period 1886–95, followed by below average values until 1930. A second period of high activity started in 1931 and has continued to the end of the record included in this study. This distribution is not an accidental result of the selection of intervals. During the period from 1910 to 1930, the seasonal storm frequency was below average in 16 of the 20 years. Since 1931, frequencies below average have been observed only four times.

Figure 2 suggests a search for periodicities and correlations with slowly varying parameters, such as sunspots. Several attempts at such correlations have been tried but proved unsuccessful.

MONTHLY FREQUENCIES

Figure 3 contains isolines of total monthly storm frequency for the 64-year period analyzed. These lines indicate how often a storm has passed through each 5° latitude-longitude square. Comparison of the frequency in any square with the total number of storms observed during the month gives information which could be used in risk determinations. For example, the square extending from 25° N. to 30° N. and from 80° W. to 85° W., which comprises most of Florida, has had nine storms in June during the 64 years. In the same period a total of 27 June storms was charted for the whole hurricane region. This means that one-third of all storms passed through this square and thus, either affected or endangered Florida (probability 0.33).

The probability of storm occurrence in a given month is indicated by the ratio of the number of months with storms divided by the total number of months—64 in our case. Table 2 shows the probability of storm occurrence for each month in three groups: One or more storms a month, two or more, and three or more. A total of 64 years is perhaps insufficient to obtain completely stable probabilities, but is the best that can be offered. As would be expected, the probability is high from August through October. In September it is almost unity. The probability that more than one storm will occur is also great during this latter month. For instance, the occurrence of three storms in September is more likely than that of one storm in June, July, and November.

TABLE 2.—*Probabilities of storm occurrences per month*

	May	June	July	Aug.	Sept.	Oct.	Nov.
At least one storm	0.09	0.34	0.39	0.75	0.92	0.83	0.36
Two or more storms	.02	.06	.11	.52	.72	.59	.03
Three or more storms	0	.02	.03	.19	.42	.34	.03

From the previous analysis the probability is 0.33 that a June storm will endanger Florida. Table 2 shows that the probability of a storm occurrence in June is 0.34. We can ask, then, the following question: What is the probability of a storm endangering Florida in June? The answer is given by the product $(0.33)\times(0.34)=0.11$.

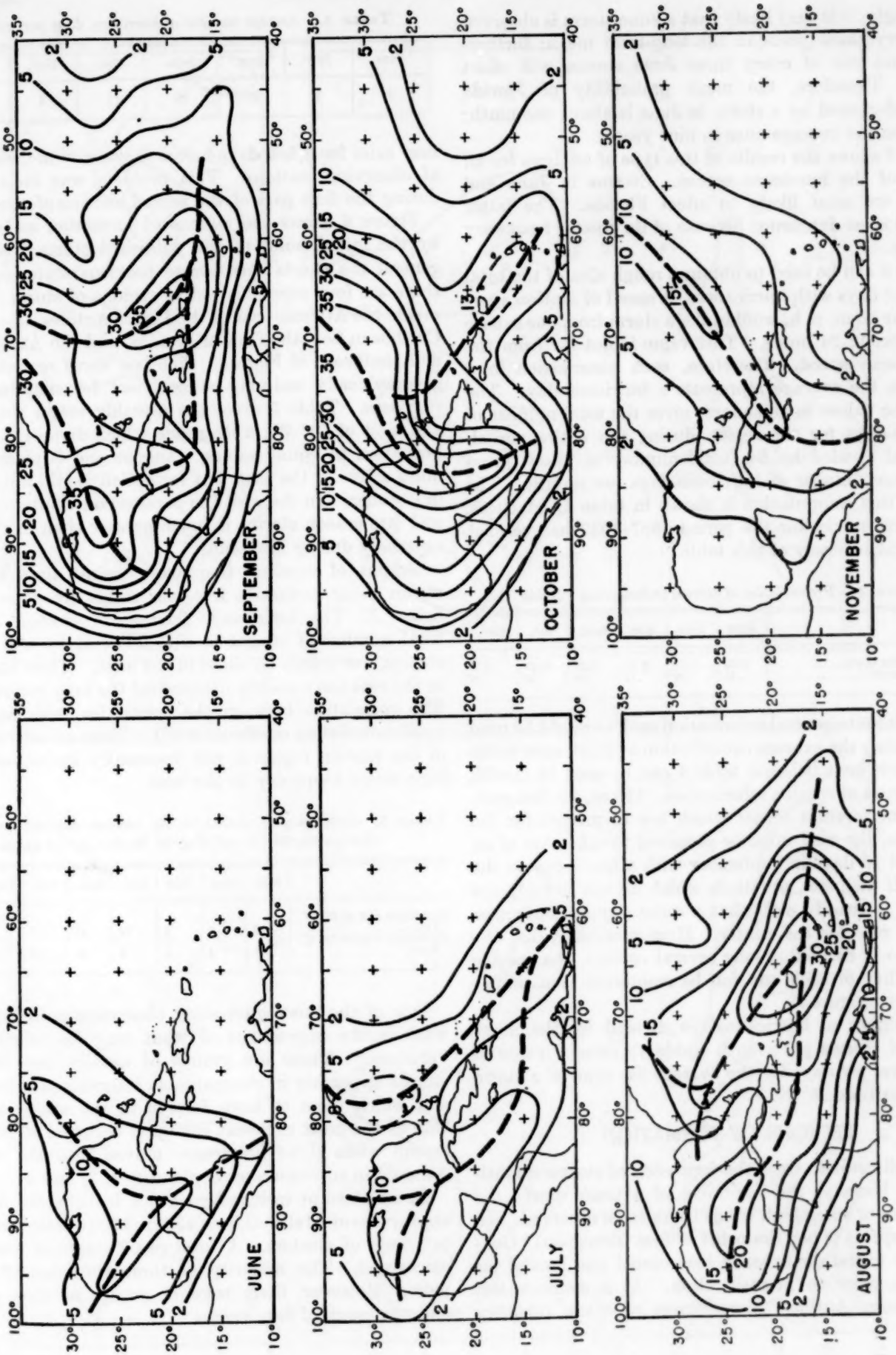


FIGURE 3.—Total frequency of tropical cyclones crossing each 5° latitude-longitude square during the 64-year period, 1887–1950. Dashed heavy lines indicate axes of maximum values.

Accordingly, it is very likely that a June storm is observed once every three years in the long-term mean; furthermore, that one of every three June storms will affect Florida. Therefore, the mean probability of Florida being endangered by a storm in June is about one ninth; that is, on the average once in nine years.

Table 3 shows the results of this type of analysis for all months of the hurricane season. Storms in June and October are most likely to affect Florida. The latter month is most dangerous because of its greater frequency of storms.

Figure 3 can be used to obtain a rough idea of the total number of days with hurricanes. A speed of motion averaging near 15 m. p. h. would take a storm from one square to the next in 24 hours. This value is not far from the actual mean speed. Therefore, each observation in a square on the average represents a hurricane-day. The sum of the values in all squares gives the total number of hurricane-days for the region during the entire period. This total divided by 64 (total number of years) gives the average number of hurricane-days per month. The result of this computation is shown in table 4. A check from storm tracks for the period 1887–1932 has verified the general accuracy of this table.

TABLE 3.—*Probabilities of storms endangering Florida*

	June	July	Aug.	Sept.	Oct.	Nov.
From an existing storm	0.33	0.21	0.15	0.21	0.29	0.11
During the month	.11	.08	.11	.19	.24	.04

In addition to general information such as might be used in calculating the average contribution of hurricanes to the atmospheric heat balance, table 4 can be used to furnish various types of specific information. Given, for instance, a hurricane forecast center which has to predict for the whole area, the staff must be prepared to take care of an average of 16 days in September with a hurricane on the charts. If incipient situations which do not develop are added, it is readily seen that a quiet day in September would be rare for the center. If responsibility for the whole area is divided among several centers, the specific responsibility of each one can be computed in a similar manner from figure 3.

The number of hurricane-days divided by the mean number of storms per month (table 1) gives a value of slightly over six days for the average life span of a storm south of latitude 35° N.

REGIONS OF FORMATION

It is difficult to treat the formation of storms quantitatively. Usually, the beginning of a track marks the point where or when high winds begin to be observed. In most cases, this is not the point of first formation. Generally, the initial disturbance has existed and moved for some time prior to intensification. As is common east of the Lesser Antilles, disturbances of storm intensity

TABLE 4.—*Average number of hurricane days per month*

June	July	Aug.	Sept.	Oct.	Nov.	Season
2	3	10	16	12	3	46

may exist for a few days before they arrive in the network of observing stations. This problem was most serious during the first part of the period because of scarce data.

Figure 4 shows the regions of formation as indicated by the initial point of the published storm tracks. In general the charts corroborate previous statements that there are four especially active regions of storm development: the Atlantic east of the Lesser Antilles, the western Caribbean Sea, the Gulf of Mexico, and the Atlantic east and southeast of Florida. The last three regions adjoin geographically and may be combined for some statistical purposes. Table 5 gives the monthly storm totals east and west of 70° W., a longitude which divides the storm formation in equal halves. August and September are most active in the east, but formation is still appreciable in October. In the west the percent contribution of early and late season storms is much greater than in the east, especially during May-June.

Graphs of seasonal frequency against time for each region using successive five-year totals are presented in figure 2. The long-range fluctuation evident for the total number of storms is well followed by the eastern storms, but poorly by those in the west. Thus variations in the east have mainly determined the long-period trend. The correlation between the curves for both regions is small (correlation coefficient 0.05). Thus an active season in the eastern region is not necessarily accompanied by high storm frequency in the west.

TABLE 5.—*Frequency of storms in the eastern Atlantic and in the western Caribbean and Gulf of Mexico per 10 years*

	May	June	July	Aug.	Sept.	Oct.	Nov.	Total
Formation east of 70° W. long	0	0	2	12	14	7	2	37
Formation west of 70° W. long	1	4	3	4	10	12	2	36

One of the most interesting observations in hurricane work is the appearance of what may be called storm "clusters." These are groups of usually two or three storms appearing in succession at intervals of a few days and which seem to have formed in the same location. One of the most clear-cut examples occurred in the 1951 season when three hurricanes moved into the western Atlantic in succession on September 2, 3, and 5.

In an attempt to investigate this feature, the dates of appearance of all storms from 1886 to 1950 were investigated in search of clusters. A total of 59 clear-cut cases was discovered. The majority of these consisted of storm pairs. However, there were 11 groups of three storms and one group of four storms.

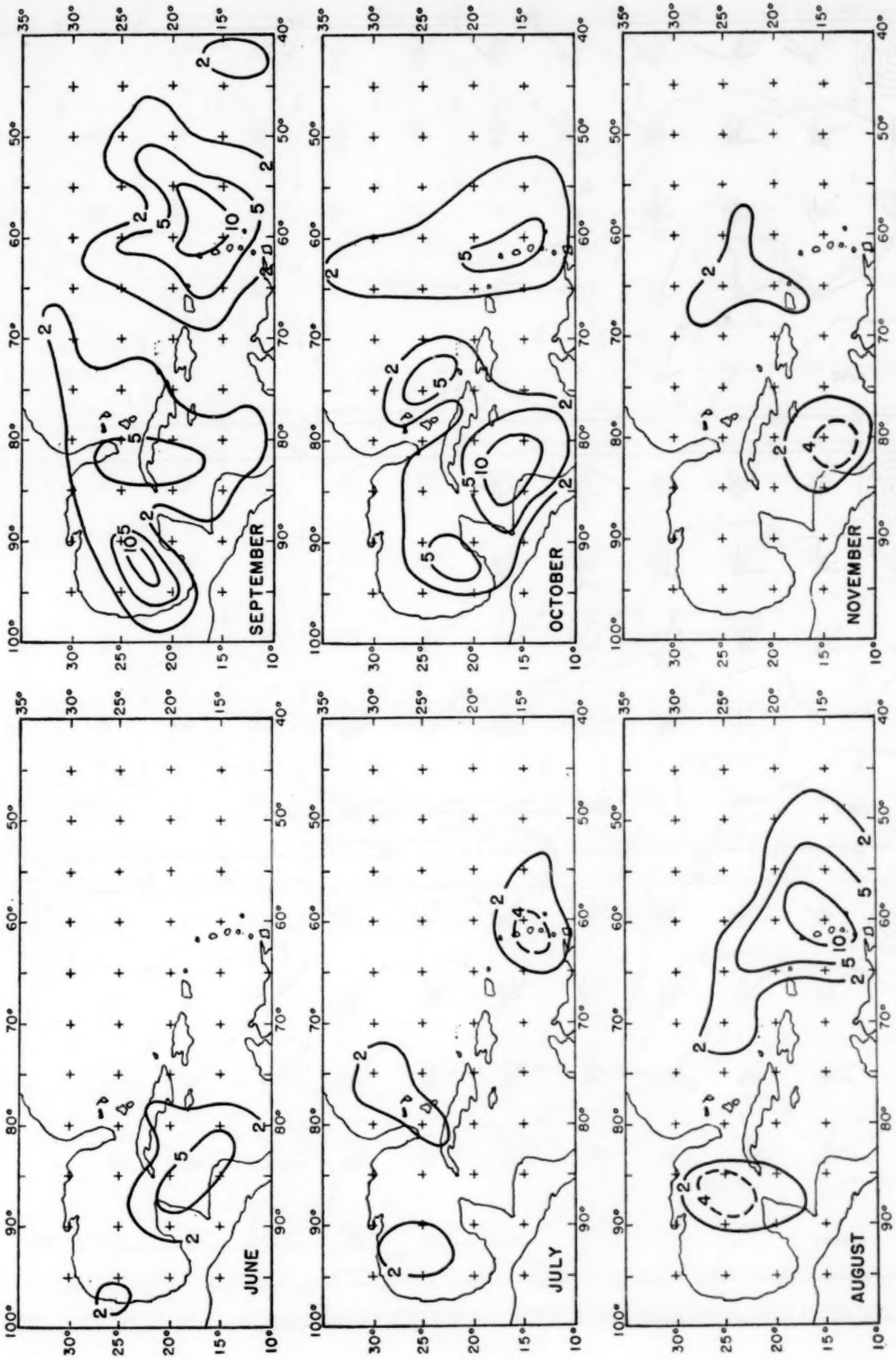


FIGURE 4.—Total frequency of tropical cyclones with track starting at each 5° square during the period 1887–1950.

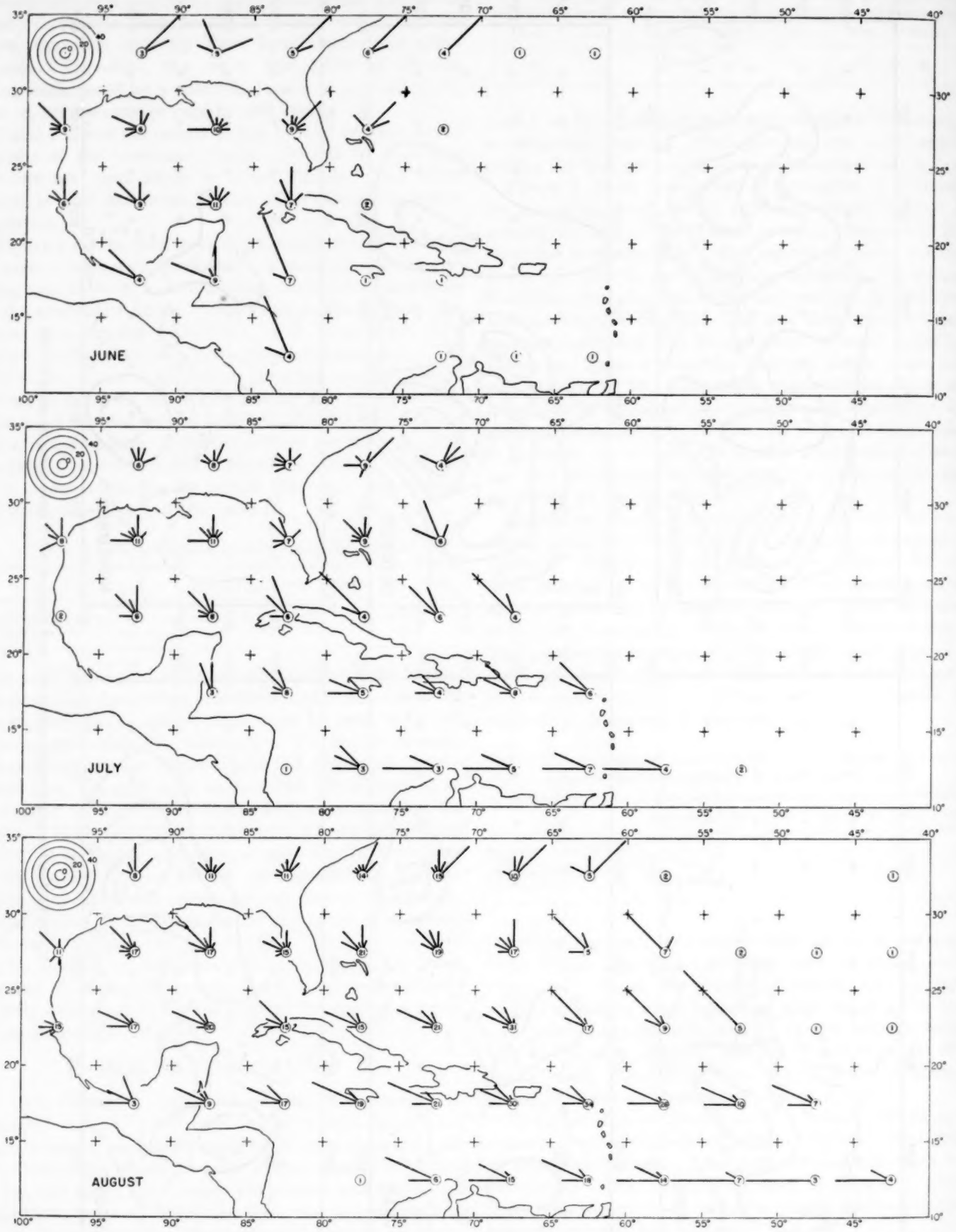
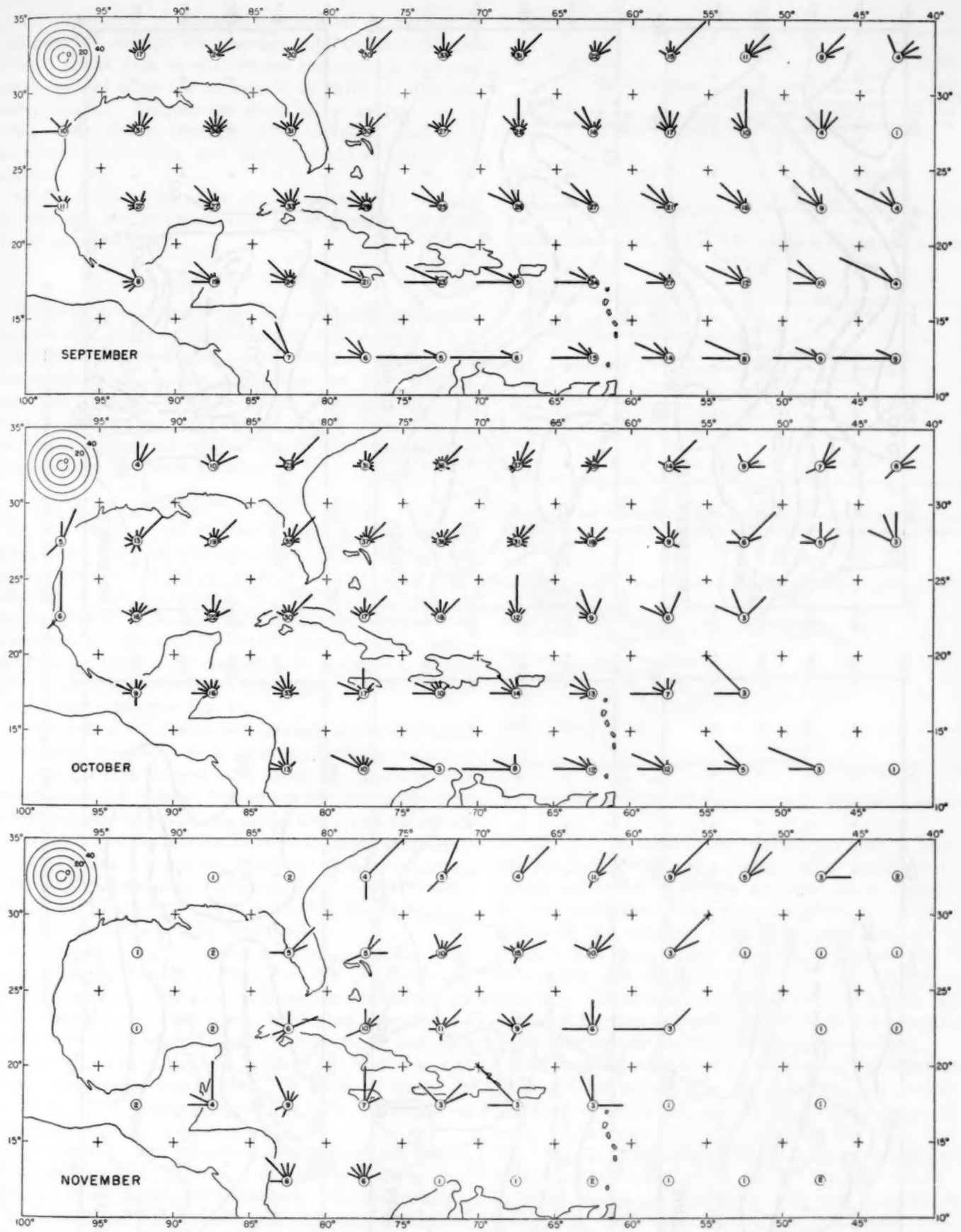


FIGURE 5.—Percentage frequency distribution of the direction of motion of tropical cyclones by 5° squares. The number in the inner circle represents the number of storms observed



in each square. The length of each vector gives the percentage frequency of storms moving in a 22½° sector centered at that direction. Scale is shown in upper left-hand corner.

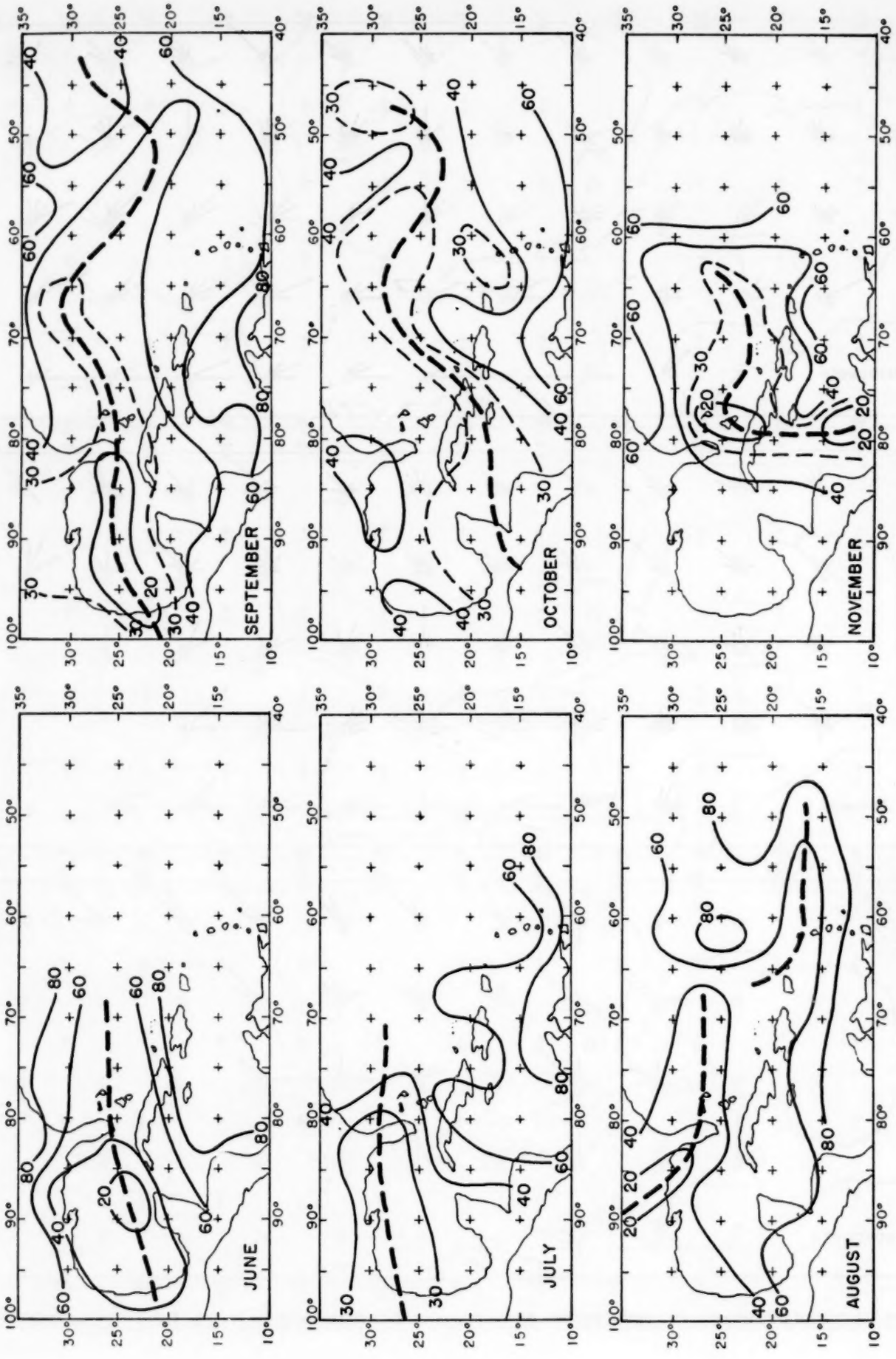


FIGURE 6.—Percentage frequency of motion along the modal direction. Heavy dashed lines represent axes of minimum frequency.

The frequency of clusters was highest in September (38 percent), August (28 percent), and October (21 percent). If the data on clusters are combined in five-year totals as was done for all storms in figure 2, a similar curve results. Frequencies were below average up to 1930, then above average. This suggests that high hurricane frequencies are partly produced by storm clusters.

Of the 59 cases, 41 or 70 percent occurred in the east indicating a definite preference for clusters in the Cape Verde group of storms.

MOTION OF STORMS

Preparation of average hurricane tracks has been undertaken many times. Outstanding is the work of C. L. Mitchell [1] who presented a set of monthly charts giving the resultant directions of motion by 2½° latitude-longitude squares. Even with an accumulation of 26 more years of data, an increase of 100 percent in the amount of factual information, we do not feel that these charts can be improved greatly.

DIRECTION OF MOTION

In our study of the motion of storms, direction and speed have been treated separately. The directions of motion were tabulated in each 5° square using 22½° direction sectors centered at W., WNW., NW., etc. (16 cardinal points). The interval of 22½° was chosen because it was not so large that the results would become useless but large enough for the samples to be significant. From the tabulation, percentage frequencies of direction of motion were computed (fig. 5).

Inspection of the charts immediately shows the modal direction of motion in each square. The significance of the mode is directly available since the length of the arrows gives the percent frequency, also the probability of storm displacement in the modal and other directions. The reliability of figure 5 is affected only by the magnitude of the samples. These are relatively great in August, September, and October. In June, July, and November, the number of observations is small, but the patterns in these months still are fairly consistent.

In forecasting, figure 5 has most value in the early stages following detection of a storm. In the absence of other information, it is logical to predict a track along the modal direction. Figure 5 also tells what directions of motion should not be predicted. In August, for instance, no storm of record in the area south of 25° N. and east of Florida has moved east of north or south of west. It would be quite illogical to predict such an abnormal path without most cogent reasons.

The confidence in a prediction of a modal track can be estimated from the percentage frequencies of the modes. These are shown separately in figure 6. We note maxima in the lowest and highest latitudes, with an intermediate axis of minimum frequency situated mostly between

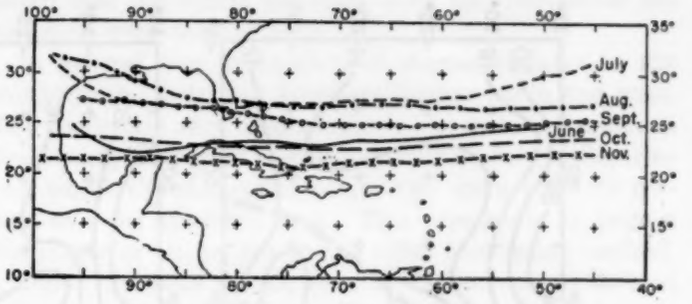


FIGURE 7.—Mean monthly position of the latitude of the subtropical ridge line at 700 mb. [4].

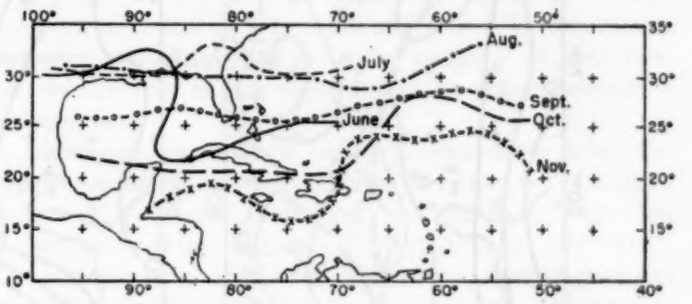


FIGURE 8.—Lines showing latitude of modal direction of motion of 360° in each month. South of these lines storms move mainly with a component toward west, to their north, toward east.

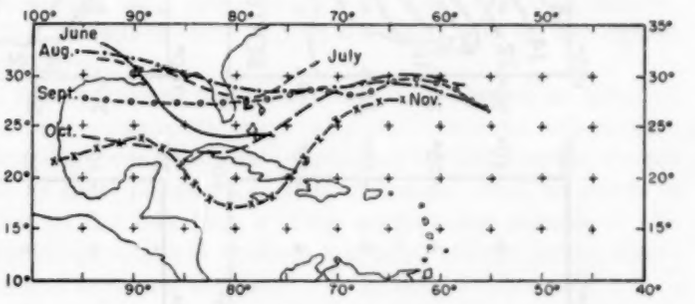


FIGURE 9.—Lines showing latitude of modal occurrence of recurvature in each month.

20°–30° N. In some areas, notably the Gulf of Mexico, one can hardly speak of a mode. Weak double or triple modes are found in several squares. Here, figure 6 is without usefulness. The statistics reflect the large variability of the synoptic weather pattern over the Gulf region. The mean trough aloft, which lies over the Gulf in summer, and the subtropical ridge line oscillate considerably. Since the motion of storms is largely determined by the flow patterns aloft, the lack of a pronounced modal direction in the Gulf area is understandable.

The seasonal changes of the latitude of the subtropical High also are indicated in figure 6 since the position of the axes of minimum modal frequency correspond in parts of the area to the position of the ridge line at 700–500 mb. The monthly shift of the subtropical ridge follows a regular course (fig. 7) [4]. It lies near 23° N. in June, moves northward in July and August, then southward until November. The minimum axes of figure 6 undergo similar displacements.

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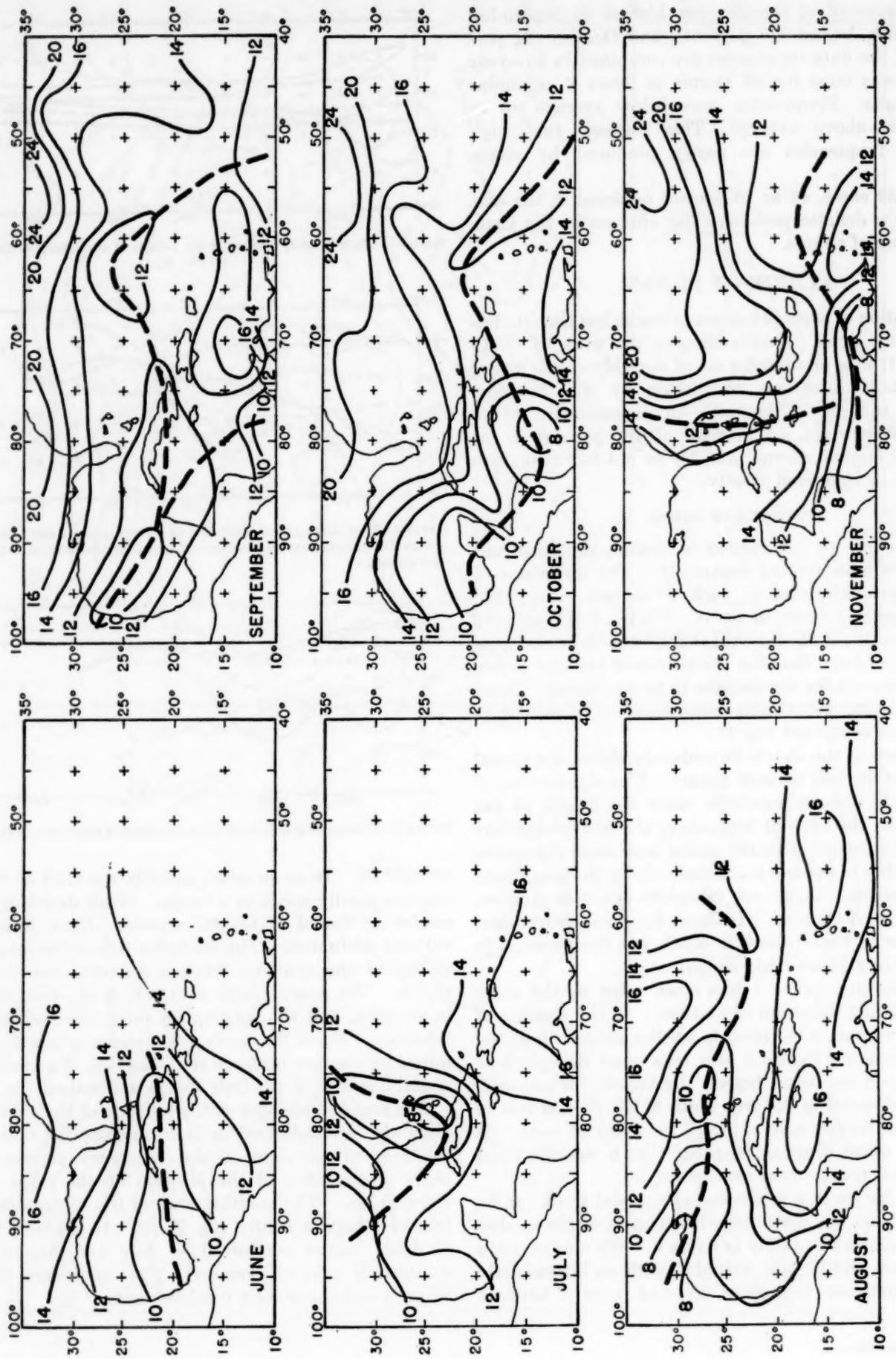

FIGURE 10.—Median speed of motion (m. p. h.). Dashed heavy line shows axis of slowest median speed.

The relation of the subtropical ridge to the storm movement becomes even plainer if we plot (1) lines connecting squares with a modal direction of 360° in each month (fig. 8), and (2) lines connecting squares with maximum frequency of recurvatures (fig. 9). For the latter purpose the westernmost point in the track of a recurving storm was considered as the point of recurvature.

The patterns of figures 8 and 9 are fairly similar. By and large the axes shift in accord with figure 7. But we also note considerable irregularities. Presumably the axes of figures 8 and 9 reflect the position of the subtropical ridge on days when a recurvature took place, while the means of figure 7 are for all days. Comparing figures 7–9 quantitatively on this basis, we find that the subtropical ridge lies on the average 2° latitude farther north on days with recurvature than in the monthly mean.

SPEED OF MOTION

The median values of the speed of motion in each square are shown in figure 10. An axis of minimum speed lies roughly between 20°–30° N. with higher speeds to the north and south. In the southern belt, below 20° N., the average speed is 14–16 m. p. h. North of 25°–30°, we observe 14–16 m. p. h. during June, July, and August, increasing to over 20 m. p. h. in September, October, and November. This increase coincides with the southward shift of the latitude of recurvature and is due to the well-known fact that storms usually speed up considerably on the northeast track after recurvature.

Mean deviations from the values in figure 10 were computed and analyzed. Motion is fairly constant in the belt 10°–20° N. and in the Gulf of Mexico. Mean deviations are of the order of 2 to 4 m. p. h. during the whole season. Variability is much greater in the north as the mean deviation increases from 4 m. p. h. in June and July to well above 6 m. p. h. in September, October, and November.

PERSISTENCE COMPUTATIONS

One of the main objectives of this study was to determine the probability of success of linear extrapolation. The results presented here are based on persistence of direction. In each square the change in direction of motion between two successive 24-hour periods was tabulated. Looking downstream, the change was considered positive if the storm moved to the right of its previous path, and negative if it moved to the left. For example, if a storm moved in the direction 300° in the initial 24-hour period and 320° in the subsequent period, the angle of change was recorded as +20°. A storm track was considered persistent when the change was within ±10°.

From the tabulated data, the percentage frequency of persistent storms was calculated in each square for each month. Figure 11 shows the results, which can be interpreted as giving the probability of success of straight-line extrapolation. In using figure 11, it should again be noted that the charts for June, July, and November are based on very limited data.

In general, the probability of success is large in the southernmost belt, but decreases farther north and west. The results are very encouraging in the eastern Caribbean Sea during the period of greatest danger, July to September, where the chances of persistence are around 80 percent over an extensive area. This represents as large a confidence as can be put on any other forecasting method, a happy outcome for an area in which, due to lack of adequate upper-air data, climatology and persistence serve as important tools of prediction.

In the Gulf of Mexico and adjacent regions persistence is a poor indicator of future storm tracks. In this region, however, upper-air data are more plentiful so that forecasters can rely to a greater extent on other forecasting techniques.

Additional persistence computations were tried for subgroups of the samples. The persistency of storms moving in a direction 270°–300° was compared with that of storms moving between 300°–330° and 330°–360°. The results as far as regional distribution is concerned did not differ significantly from those indicated in figure 11. There was, however, a significant tendency for storms moving on west to west-northwest tracks to be more persistent than those moving on more northerly tracks. This particular computation was tried only for the month of August.

Computations were made also with respect to speed of motion. Again, the regional distribution did not change, but there was a noticeable tendency for fast moving storms to be most persistent. This statistical result no doubt is due to the fact that a given acceleration normal to the previous path will produce a smaller change in the direction of motion if the speed is large than if it is small.

Deviations from persistence were also investigated. Most often storms curved to the right. In some regions, particularly over the western Gulf of Mexico changes to the left also were numerous. In the north the frequency of nonpersistent storms exceeds that of persistent storms. The angle of change in the direction of motion of the nonpersistent storms was tabulated and the median of the distribution determined separately for the positive and negative turnings. This median value was then plotted for each square (fig. 12). Reasonable patterns were obtained for all months. In the south the angle of change is smallest. A belt of maximum change lies close to the subtropical ridge line. Values decrease again farther north. The relation of the axes of maximum turning to figures 6–9 requires no elaboration.

Figure 11 applies only to straight-line persistence. Other types of persistence can be defined. For instance, one can ask the question to what extent curving storms maintain the same path curvature. This computation would involve higher order derivatives. In view of the uncertainties even in the best storm tracks, no further work was attempted.

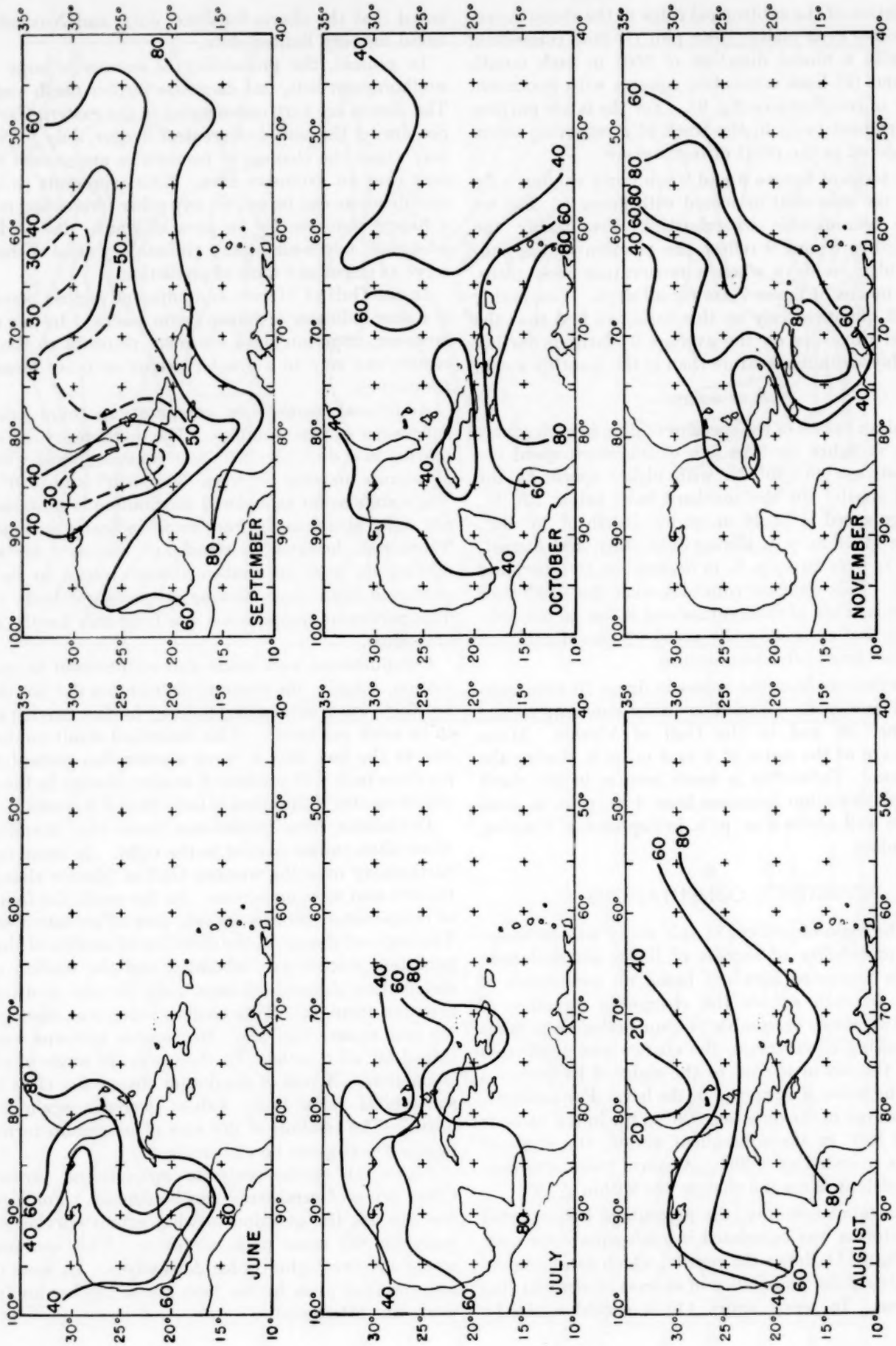

FIGURE 11.—Percentage frequency of storms moving on a persistent track.

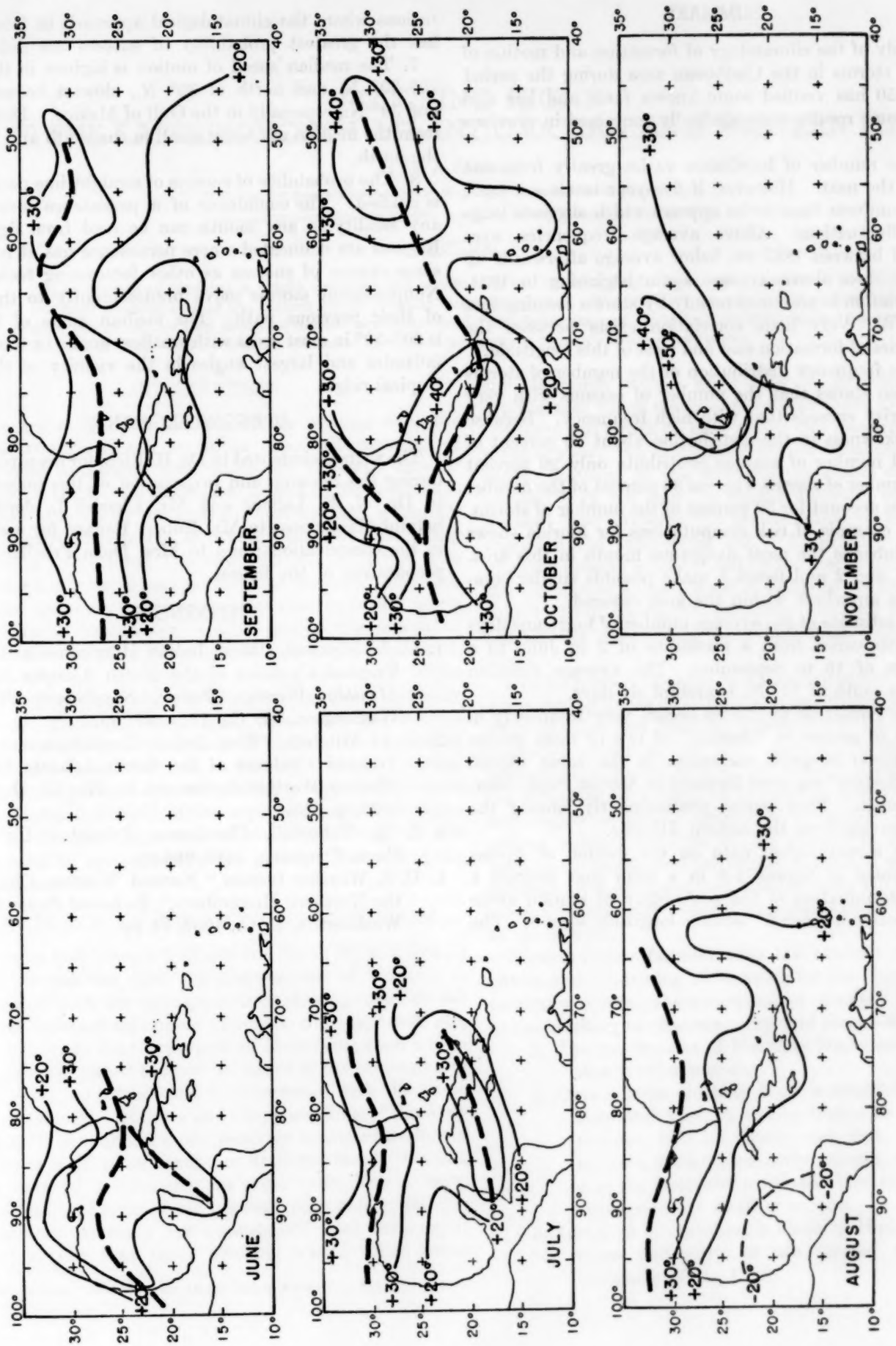

FIGURE 12.—Median angle of change in direction of motion of nonpersistent storms. Dashed heavy lines indicate axes of largest median angle.

SUMMARY

A study of the climatology of formation and motion of tropical storms in the Caribbean area during the period 1887–1950 has verified some known facts and has also shown some results not specifically contained in previous works.

1. The number of hurricanes varies greatly from one year to the next. However, if five-year totals are used, a more uniform time series appears which suggests long-period fluctuations. Above average frequencies were observed between 1887–95, below average afterwards up to 1930, then above average again beginning in 1931. This variation is produced mainly by storms forming east of 70° W. Very little correlation exists between the frequencies of formation east and west of this longitude.

2. The frequency distribution of the number of storms per season shows that the number of seasons with very low activity exceeds that with high frequency. Because of this skewness in the distribution about 40 percent of the total number of seasons contribute only 20 percent of the number of storms whereas 30 percent of the number of seasons account for 50 percent of the number of storms.

3. An example of risk computations for Florida shows that October is the most dangerous month in this area. Tables 1 and 2 and figure 5 make possible similar computations anywhere within the area covered.

4. An estimate of the average number of hurricane days per month varies from a minimum of 2 in June to a maximum of 16 in September. The average duration of storms south of 35° N. is around six days.

5. The formation of storms occurs very frequently in the form of groups or "clusters" of two or more storms which appear in quick succession in the same region. These "clusters" are most frequent in August, September, and October. They occur predominantly among the storms moving from the eastern Atlantic.

6. The climatological data on the motion of storms are presented in figures 5–6 in a form that permits a quick determination of the probability of motion along each direction at each 5° latitude-longitude square. The regions where the climatological approach in forecasting has the greatest probability of success are delineated.

7. The median speed of motion is highest in the belts 10°–20° N. and north of 30° N., slowest between 20° and 30° N., especially in the Gulf of Mexico. Deviations from the median are fairly small in the south and large in the north.

8. The probability of success of straight-line persistence is studied. The confidence of a persistence forecast at any locality in any month can be read from figure 11. Regions are delineated where persistence has at least the same chance of success as other forecasting techniques. Nonpersistent storms move predominantly to the right of their previous path. The median angle of turning is 20°–30° in most areas with smallest angles in the lowest latitudes and largest angles in the vicinity of the subtropical ridge.

ACKNOWLEDGMENTS

The writer is indebted to Dr. H. Riehl for his supervision during the research and preparation of this manuscript; to Dr. N. E. LaSeur and Mr. Charles L. Jordan for helpful discussions; to Mr. Robert Renard for assistance in the computations; and to Mrs. Della Friedlander for preparation of the figures.

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BLOCKING HIGHS OVER THE EASTERN NORTH ATLANTIC OCEAN AND WESTERN EUROPE

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ABSTRACT

The concept of blocking is briefly reviewed and a definition of "blocking High" in terms applicable to the daily sea level weather map of the eastern North Atlantic Ocean is adopted. The monthly frequency and geographical distribution of blocking Highs as defined are determined from forty years of Historical Weather Maps. Several features of these distributions are discussed in relation to observed monthly weather variations.

INTRODUCTION

The major synoptic features of the weather over the North Atlantic Ocean are often described in terms of their close connection with either the Icelandic Low or the Azores High. An essential attribute of the dominance of these systems in the synoptic picture that is usually visualized is the concept of a broad band of "prevailing westerlies" separating the two. At the outset of this discussion it is important to recognize, however, that such features are most prominently displayed on mean charts and that in day-to-day weather maps this simplified picture is more often than not considerably complicated, particularly by the presence of large stationary Highs in the region where the prevailing westerlies are normally located. These surface Highs, which are the subject of study in this report, can thus be considered as impeding the usual westerly flow and as forming a "block" around which other pressure systems such as troughs and cyclones must detour. Because of the important part these Highs play in the mechanism referred to as "blocking," it will be helpful to review briefly the principal features of the mechanism.

DISCUSSION OF THE BLOCKING MECHANISM

Namias and Clapp [1], Elliott and Smith [2], and Rex [3] have pointed out that the phenomenon of blocking is associated with the retrogression or slowing down in the normal eastward movement of ridges, troughs, Lows, etc. The definitions for the purpose of identifying such a phenomenon are varied to meet the needs of the investigators writing on the subject and in accordance with the scope of their studies. Namias and Clapp conclude, "Blocking operates in the form of a progressively westward decline in the speed of the zonal circulation at 10,000 feet." Or, in a later work [4] in discussing the index cycle, Namias says, "Since an exchange of air between pole and equator is an obvious necessity for atmospheric heat balance, it would appear that those blocking waves which occur simultaneously with a great reservoir of cold polar air are the ones which materialize into an index cycle."

Elliott and Smith [2] have stated this idea from another point of view: "An explanation for the dynamical development consisting of the abnormal extension of the subtropical high cell into the region normally occupied by westerly flow involves the accumulation of heat in the region of the subtropical cell." Later they say, "The blocking process is postulated as the mechanism by which the circulation adjusts itself in order to redistribute this heat." Both viewpoints recognize blocking action as a process for distributing abnormal heat loads between zones.

Rex [3] related blocking to a splitting of the jet stream. After setting limits as to time and geography, he recorded cases to show how blocking occurs when this split in the westerlies exists at 500 mb. Rex, in reviewing some theoretical work by Rossby [5], further postulated that the initiation of a block is impossible downstream from any region in which subcritical velocities exist. The critical velocity depends on the change in the Coriolis force to the north, and the square of the half-width of the stream. Rex further stated that blocking will be initiated when a "sufficiently intense" cyclonic impulse is imparted to the system.

Meteorologists familiar with the analysis of synoptic charts and the issuing of forecasts for the North Atlantic recognize several characteristics of possible importance in the blocking mechanism. Some of these are as follows:

1. The movements of blocking Highs are relatively slow from day to day.
2. Once a large blocking High is established, it persists and when it finally begins to break, the pressure falls off slowly each day. This slow process, if identified early enough, might then give the forecaster a valuable clue as to the persistence of the weather regime.
3. Lows, on approaching a blocking High, either become stationary or are steered around the periphery of the High.

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From the preceding discussion there seems to be some need of more knowledge concerning the part blocking Highs play in the general circulation. The purpose of the present investigation is to determine the frequency and geographical distributions of blocking Highs over the eastern North Atlantic and western Europe and through a discussion of the results to study the characteristics of blocking throughout the seasons.

However, in order that these as well as other aspects of this problem can be investigated, it becomes necessary to provide some sort of objective definition of blocking, avoiding where possible time-consuming derived and computed observations, and at the same time attempting to suit the special requirements of a forecast office that deals with the day-to-day problem of forecasting the weather over the North Atlantic.

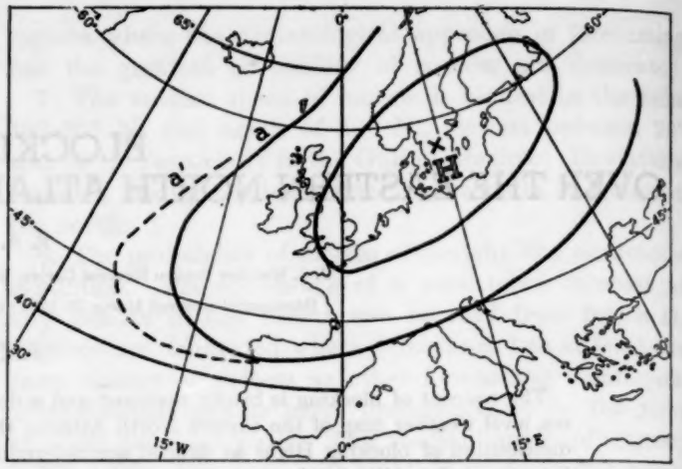

FIGURE 1.—Illustration of the 24-hour displacement (*a* to *a'*) of an isobar in the western lobe of a High, thereby defining a blocking High at the position marked X. The area between 40° and 65° N., and 0° and 30° W. is the region examined for such westward displacements in order to define blocking cases for the purposes of this study.

DEFINITION OF BLOCKING

The Daily Synoptic Series, Historical Weather Maps (Northern Hemisphere, Sea Level) was examined chart by chart for the period 1899–1938. If within the area bounded by latitudes 40° and 65° N. and between longitudes zero and 30° W. any isobar on the western lobe of a High (see *a* in fig. 1) moved west (in fig. 1 to *a'*) or remained in the same position on the following day, then by definition an instance of blocking was said to exist, the associated High was identified as a blocking High, and its position [2] and central pressure were recorded. Thus, for the hypothetical instance shown in figure 1, the position recorded would be 58° N., 14° E.

The results of recording the blocking Highs, as defined, for the period 1899–1938 are presented and discussed in the following sections.

MONTHLY MEAN PRESSURE AND FREQUENCY OF THE BLOCKING HIGHS

The average central pressure of the blocking High by months is shown in figure 2a. Each month represents an average of 275 cases. The smoothness of this annual curve with its single maximum in January and the single minimum in August is interesting when compared with the elevation of the sun through the year. The lag of the minimum following the summer solstice is longer than that of the January maximum following the winter solstice. However, the meaning or value of this curve may be questioned when it is noted later in the report that the frequency of blocking Highs centered over the land as compared with those over the ocean varies with the seasons.

Figure 2b shows in the mean the percentage of days on which blocking Highs occurred in each month. Unlike the single wave of figure 2a, this curve shows four waves

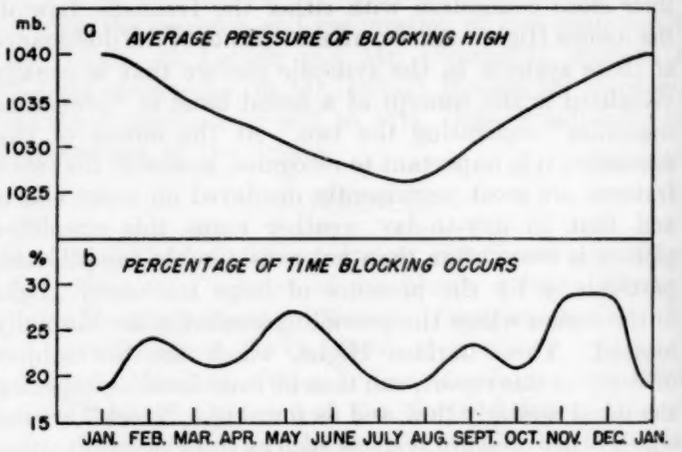

FIGURE 2—(a) Annual variation of average central pressure of blocking Highs (1899–1938), (b) Annual variation of percentage frequency of blocking Highs.

for the year, with a major maximum in November and December followed by maxima in February, May, and September. The time intervals between maxima are 2½, 3, 4, and 2½ months. This shows an increase in conditions associated with blocking in the late fall and early winter, while from December through summer to September there is an average decay. This suggests a sort of "condenser action" on an annual scale similar to that which Namias [4] has suggested happens at the beginning of an index cycle.

The low percentage of days with blocking Highs in January as compared with December may seem odd to those who watch Atlantic weather. A re-check of this month however, shows that blocking does occur, but more often is displaced to the east and does not affect the area under consideration. January circulation as shown by the normal sea level chart [6] is characterized by strong

[2] In a few cases a High was located west of the specified area (e. g., west of Greenland), but there was a ridge which extended southeastward into the area and which then moved westward. These Highs also were recorded as blocking Highs. Examples of these may be found by inspection of synoptic charts for May 11, 1909 and May 29, 1936.

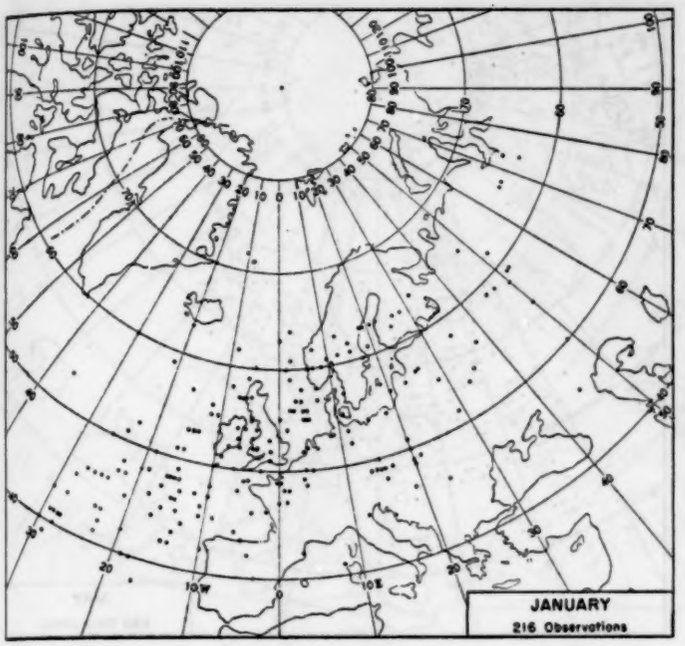

FIGURE 3.—Positions of the 216 blocking Highs observed on daily maps, January 1899–1938.

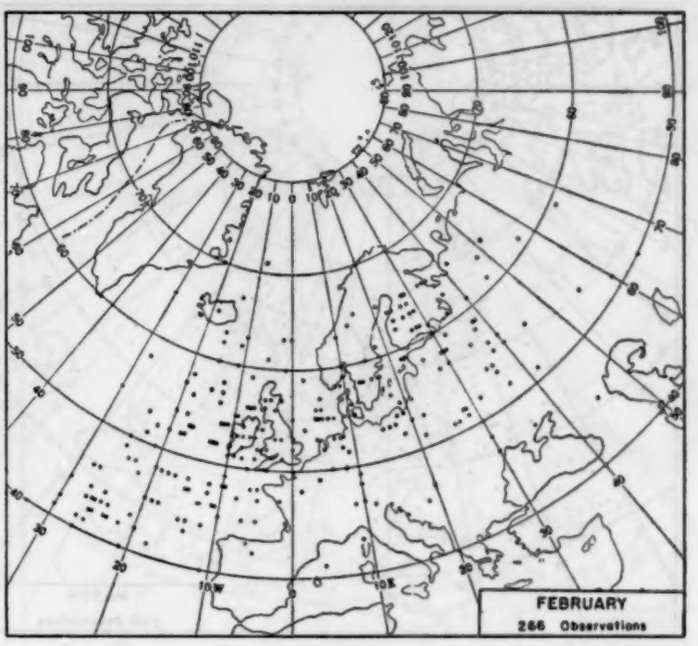

FIGURE 4.—Positions of the 266 blocking Highs observed on daily maps, February 1899–1938.

westerly flow across the Atlantic and cyclonic activity is at its height for the year.

GEOGRAPHICAL DISTRIBUTION OF BLOCKING HIGHS BY MONTHS

Figures 3 through 14 show the central positions of the blocking Highs as located in accordance with the definition of blocking mentioned earlier.

January (*fig. 3*)—The centers of the 216 blocking Highs lie on a band extending from the Azores to England, and to the North Sea, thence spreading over eastern Europe and western Asia. There are very few cases in the vicinity of Iceland as the Icelandic Low is strongest in this month. Though January on the average has a low number of cases of blocking, some years did have a high number; e. g., January 1907, 1917, 1929, and 1935. During these years the mean monthly temperatures were below normal for the British Isles, the Low Countries, Norway, and Sweden and above normal for Iceland [8]. This same pattern was true in February 1909, 1921, 1929, and 1932 when a high percentage of blocking days during the month existed along with below normal temperatures for eastern and southern Europe, near normal for the British Isles and Norway, and above normal for Iceland.

The cold flow from the east becomes a conservative part of the weather map when once established. In the January months, when there are only a few days of blocking, the temperatures are higher than normal on the Continent and generally colder in Iceland. In the latter case the westerly component would of course be stronger.

February (*fig. 4*)—The axis of points moves slightly northward during February, extending from near the Azores as an anchor point northeast to Ireland, then east over the North Sea to Poland and Finland. There are more cases in February (266) than in January (216), noteworthy increases occurring over the Baltic and near Ireland. The mean temperatures are lower in February at Leningrad and Helsinki than in any other month [8] and blocking seems to be associated with this cold spot. At the same time the westerlies over the Atlantic diminish, particularly in the north central part of the Atlantic. [6]. The Highs over eastern Europe retrograde and blocking becomes more frequent around Ireland and nearby waters. Namias' [4] description of the index cycle also shows that the major polar outbreak of the year occurs in February attended by blocking and pronounced meridional flow.

March (*fig. 5*)—Blocking diminishes in March (260 cases) and there is no definite band of blocking Highs as in January. The positions are removed farther to the north, into the Norwegian Sea and eastward into Finland. There are fewer cases over continental Europe, particularly France and Germany. In the months that do have a high number of blocking Highs there is no good relation to mean temperatures as was the case in January and February.

April (*fig. 6*)—By April, blocking has almost ceased on the Continent except in the Gulf of Bothnia area and is now confined to the waters from the Azores northward off Ireland and into the Norwegian Sea. Altogether there are 257 cases. A few are as far north as the Arctic;

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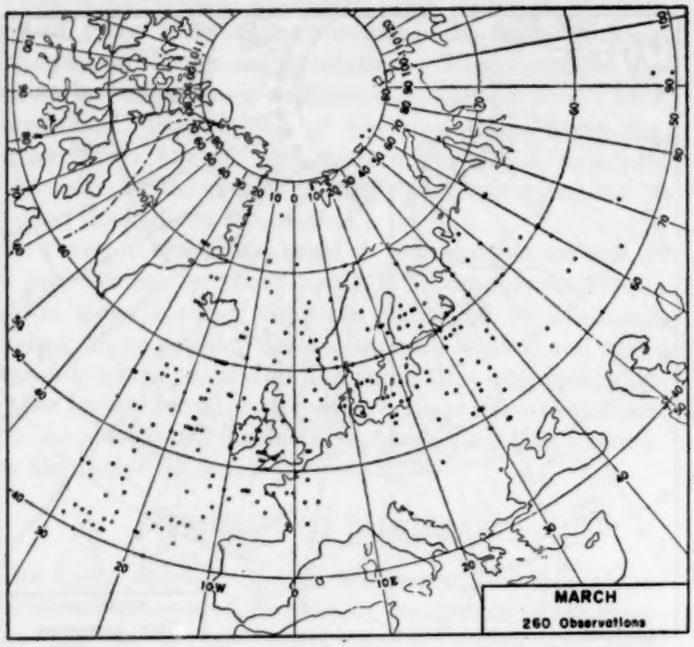

FIGURE 5.—Positions of the 260 blocking Highs observed on daily maps, March 1899–1938.

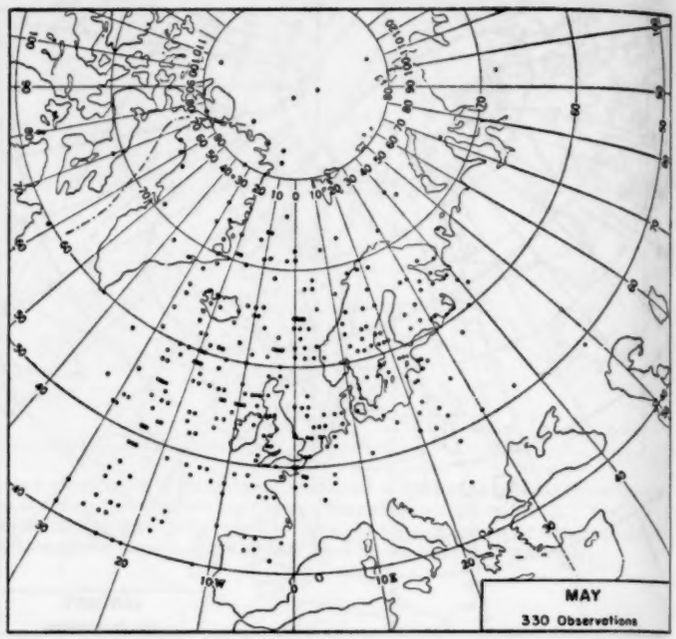

FIGURE 7.—Positions of the 330 blocking Highs observed on daily maps, May 1899–1938.

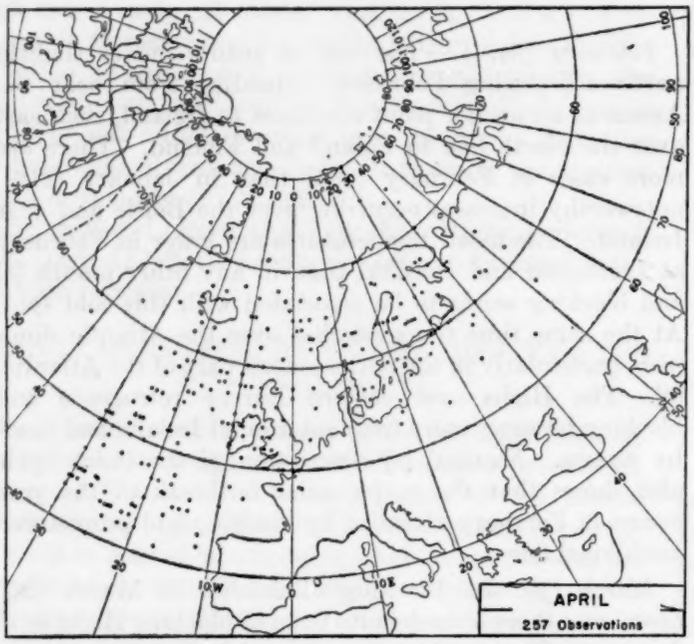

FIGURE 6.—Positions of the 257 blocking Highs observed on daily maps, April 1899–1938.

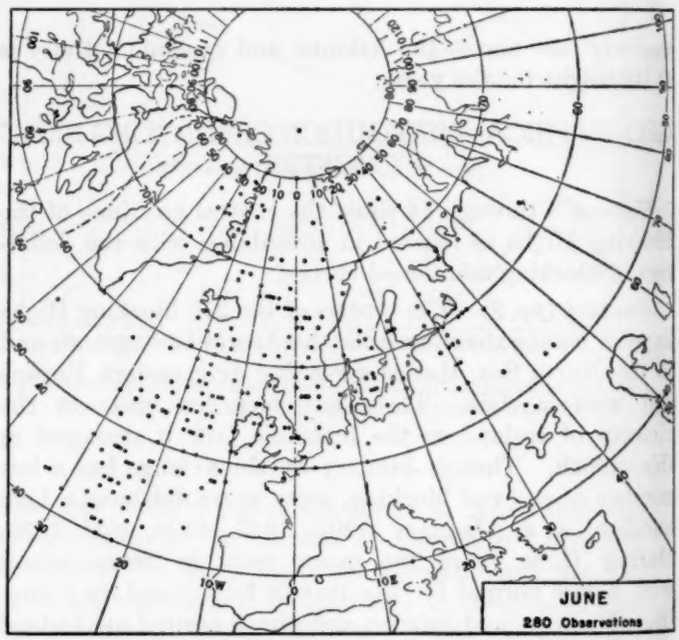

FIGURE 8.—Positions of the 280 blocking Highs observed on daily maps, June 1899–1938.

these are the polar Highs with ridges that extend southward into the area.

May (*fig. 7*)—From January to May the axis of blocking has swung from the Continent to the ocean and now shows a concentration of cases off Ireland and northeast into the Norwegian Sea. It is in this month that blocking becomes quite pronounced (330 cases). (See fig. 2b.) The Normal Weather Charts [6] shows that the 700-mb. flow in May is weaker over the area of our study than in any other month. In May, over the ocean and in western Europe, temperature gradients are weak, as shown on mean charts [6], thus permitting little modification of air masses from below. This will allow large pools of stable air to form at the 700-mb. level and below, and any upper level trough that passes through the area will likely be damped by this large body of stable surface air. In the months when there was a high percentage of blocking cases, the temperatures remained about normal over Europe except for higher values in the far north in northern Norway and Sweden [8].

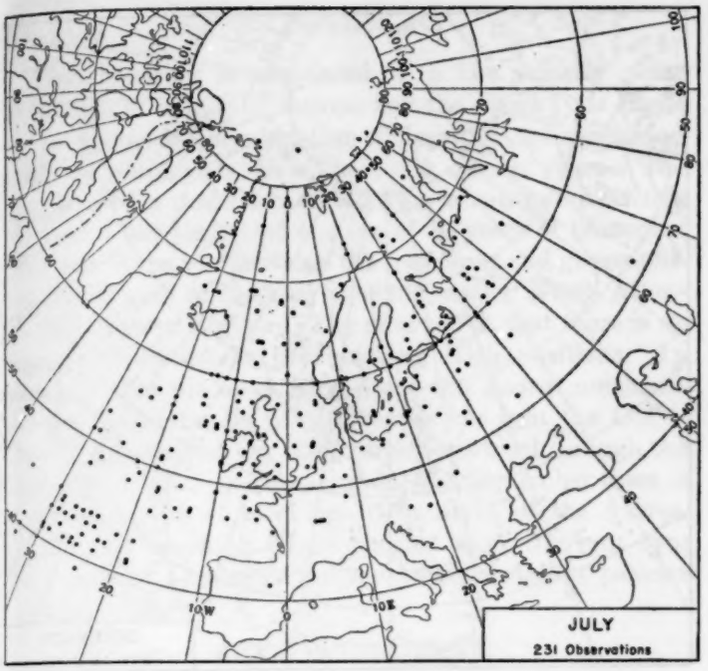

FIGURE 9.—Positions of the 231 blocking Highs observed on daily maps, July 1899–1938.

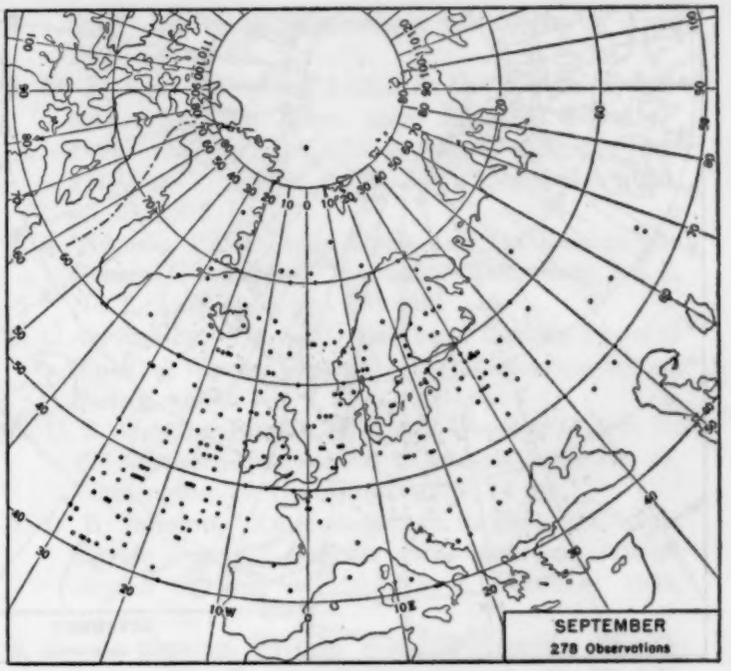

FIGURE 11.—Positions of the 278 blocking Highs observed on daily maps, September 1899–1938.

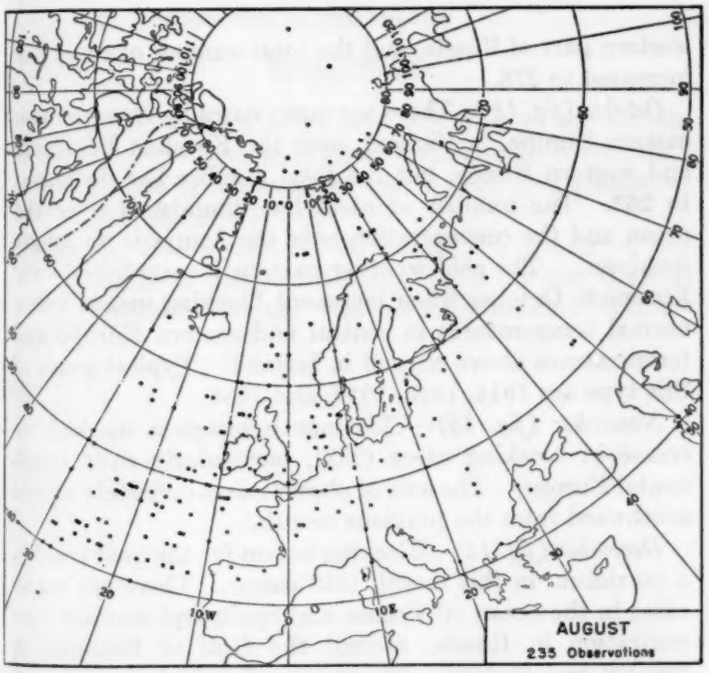

FIGURE 10.—Positions of the 235 blocking Highs observed on daily maps, August 1899–1938.

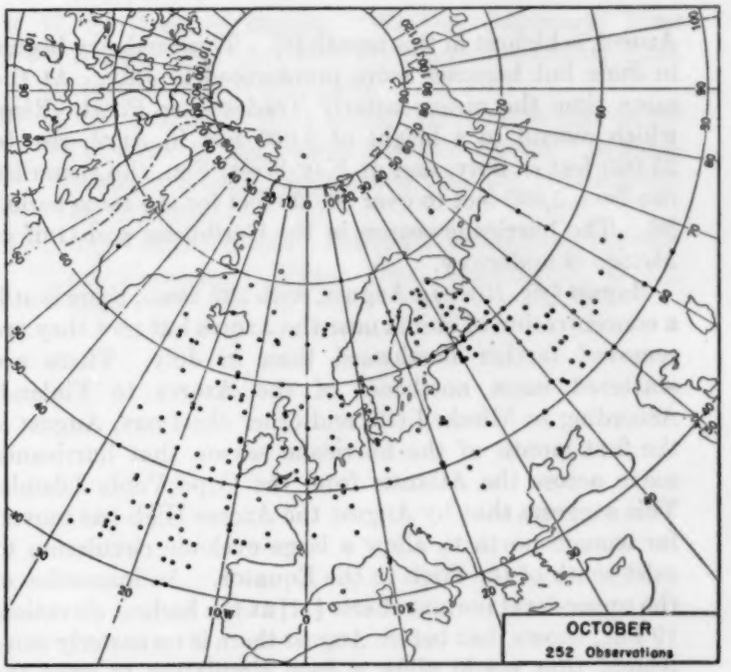

FIGURE 12.—Positions of the 252 blocking Highs observed on daily maps, October 1899–1938.

Rex [3] found that blocking reaches a maximum in April and May. His data consider about twice as many anticyclonic vortices as cyclonic; but if restricted to the anticyclonic vortices, his data show more cases of blocking in May. It is also in May that Highs stagnate over Nova Scotia and the Labrador Current. Johnson [7] has described how Highs moving across Canada from the west stagnate east of Hudson Bay when there is a warm upper level flow from the Central Plains of the United States.

June (*fig. 8*)—Blocking diminishes in June (280 cases) from the maximum in May but the positions occupy the same geographical location. There are a few less cases off Ireland and in the Norwegian Sea and a few more cases near the Azores.

July (*fig. 9*)—Aside from the overall decrease in cases (231), the most noticeable feature about July is the concentration of blocking Highs near the Azores. This is perhaps a reflection of the intensification of the Azores High at this time of year. The mean pressure at Horta,

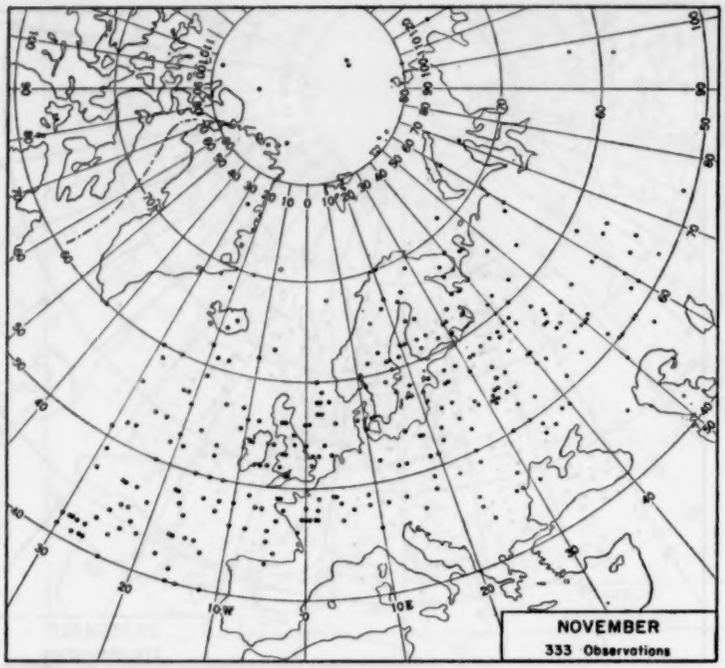

FIGURE 13.—Positions of the 333 blocking Highs observed on daily maps, November 1899-1938.

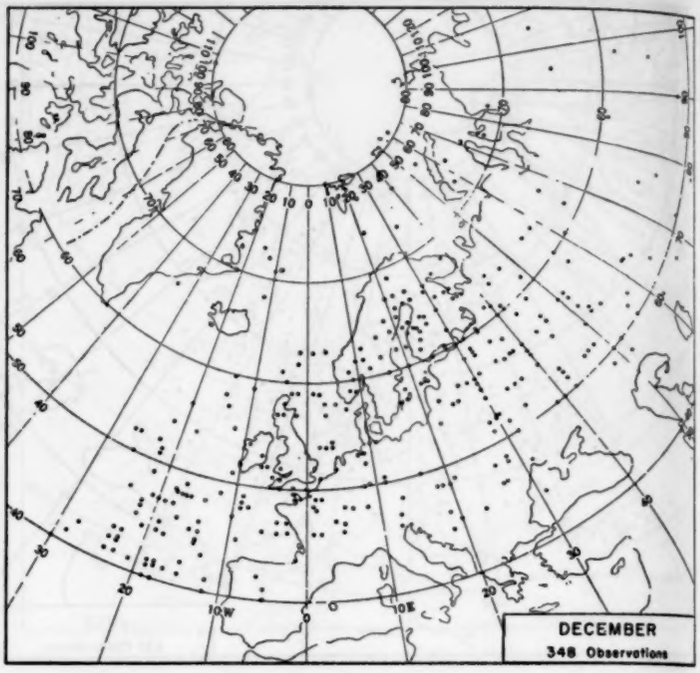

FIGURE 14.—Positions of the 348 blocking Highs observed on daily maps, December 1899-1938.

Azores, is highest in this month [8]. This tendency begins in June but becomes more pronounced in July. At the same time the mean easterly Trades over Puerto Rico, which extend to a height of 9,000 feet in April, rise to 25,000 feet in July, and at Key West, Fla., the easterlies rise from 5,000 feet to over 30,000 feet for the same period [9]. The hurricane season in the Caribbean and Gulf of Mexico is underway.

August (*fig. 10*)—In August, with 235 cases, there is still a concentration of points near the Azores but now they are removed farther northward than in July. There are scattered cases northeast of the Azores to Finland. According to Mitchell [10] and other observers, August is the first month of the hurricane season that hurricanes move across the Atlantic from the Cape Verde Islands. This suggests that by August the Azores High has moved far enough north to allow a large cyclonic circulation to exist south of the High to the Equator. An inspection of the upper-level normal charts [11] at the highest elevation, 19 km., shows that before August there is no easterly component that would allow a deep circulation to cross the Atlantic at low latitudes. An unpublished study, by the author, of tropical Lows that crossed the Atlantic from the Cape Verde Islands to the Windward Islands shows that a tropical circulation is most likely to prevail when the pressure in the Azores High is 1026 mb. or less.

September (*fig. 11*)—The Azores High block is still apparent in September but has moved northward and is centered about 46° N., 24° W. Also, there are the beginnings of blocking on the Continent, particularly in the western part of Russia, and the total number of cases has increased to 278.

October (*fig. 12*)—There are many cases by October over eastern Europe, in Finland, over the Karelian Peninsula and western Russia, but the total number has decreased to 252. The number of cases has diminished over the ocean and the concentration near the Azores is no longer dominant. The cold weather pattern is established over Europe in October when increased blocking means below normal temperatures in central and eastern Europe and temperatures above normal in Iceland. Typical years of this type are 1914, 1915, 1919, and 1936.

November (*fig. 13*)—This month brings a marked increase in blocking cases (333), particularly over continental Europe. The axis of observations definitely moves southward from the previous month.

December (*fig. 14*)—Blocking action for the year reaches a maximum in this month (348 cases). There are many cases in the ocean off France and Spain and another concentration in Russia, around the Gulf of Bothnia, in Sweden and Finland. There are a few high centers east of the Urals. In these the pressure is very high; one High was noted that reached 1070 mb. December also shows a tendency for the observations to be concentrated in a band as is the case in January. The temperature conditions over Europe are similar to those in other single winter months with a high number of blocking cases. The December months of 1899, 1902, 1933, and 1938 are good examples of frequent blocking associated with cold easterly outbreaks [8].

CONCLUSIONS

That blocking is associated with the easterly polar outbreaks of winter in Europe and the warm type Highs of the Azores or a combination of the two is the conclusion that meteorologists have held for many years. The adoption of a definition of blocking consistent with this viewpoint has permitted the use of 40 years of Historical Weather Maps to determine the frequency and geographical distribution of blocking over the eastern North Atlantic and western Europe. The data shows that there is an annual oscillation in the blocking High positions. In January they lie on a band from the Azores northeast toward Finland. By May blocking has quit the Continent and extends from the Azores northward through the Norwegian Sea. In July, August, and September there is a concentration of blocking Highs north of the Azores. In October blocking Highs become more frequent over land and by December the southwest-northeast pattern is re-established.

ACKNOWLEDGMENT

The writer wishes to acknowledge the helpful assistance of Mr. Conrad P. Mook, Research Forecaster, particularly during the preparation of this report.

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SUMMARY OF TORNADOES IN COLORADO, WYOMING, AND NEW MEXICO, 1916-51

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The infrequent occurrence of tornadoes in Colorado, Wyoming, and New Mexico, the western fringe area of the main tornado belt [1], makes the forecasting of them a difficult, and perhaps an impossible, problem. This summary is presented merely as a convenient source of pertinent facts concerning the distribution of tornadoes in these three States (the Denver Forecast District) and it is hoped it may be of some help in the public information program of weather stations in the district. The sources of data for the summary were the severe storm reports published in the Annual Reports of the Chief of the Weather Bureau (1916–34), Monthly Weather Review (1921–49), and Climatological Data—National Summary (1950–51).

As judged by property damage, there are few destructive tornadoes in Colorado, Wyoming, and New Mexico. This, of course, is a poor criterion for the severity or violence of a storm, especially in such a relatively sparsely populated area as these three States. A tornado occurring over open country and sighted from a distance might well be as violent, or more so, as one which just happened to wipe out most of a town. A tornado struck Julesburg, Colo., on June 6, 1947, and did an estimated $350,000 to $500,000 damage. This is by no means a common occurrence for in 36 tornado seasons only 11 tornadoes have been destructive enough to do estimated property damage of $50,000 or more.

A tornado in the Denver Forecast District is a relatively infrequent phenomenon. The average number of tornadoes per "tornado season" (April through September) for the years 1916–51, inclusive, is 1.42 in Colorado, 1.58 in Wyoming, and 1.00 in New Mexico, or 4.00 tornadoes per season for the district as a whole.[1] It is interesting to note that in 36 seasons there were only 18 cases of more than one tornado on the same day. This is indeed unusual when it is considered that the district has a north-south distance of over 800 miles. On five of these days there were two tornado occurrences in the same area. In only eight cases were tornadoes reported on consecutive days anywhere in the Denver Forecast District. There is only one case of record of tornadoes on consecutive days at one location, Buffalo, Wyo., on June 5 and 6, 1949, although Akron, Colo., reported a tornado on June 15, 1928, and on the following day Thurman, 35 miles south reported a tornado. Comparisons of multiple tornado situations seems to be meaningless in an area that is over 800 miles in north-south extent and has so few occurrences. No doubt many tornadoes go unreported because there is no damage. Very frequently tornado reports carry the statement "funnel did not touch the ground."

The distribution of tornado occurrences in Colorado, Wyoming, and New Mexico for April through September is summarized in the accompanying figures. Figure 1 shows the spatial distribution in the three States, tabulated by counties.[2] The bulk of the tornadoes occurred east of the 106th meridian in Wyoming and east of the 105th meridian in Colorado and New Mexico. Wyoming shows a concentration of occurrences in the southeast corner, corresponding to the concentration in the northeast section of Colorado. New Mexico shows no particular concentration except east of the 105th meridian the length of the State.

It is not surprising that so few tornadoes in this district are destructive. If the cities that are close along the mountains and very near the 105th meridian are excluded there are only two or three towns in eastern Colorado of 5,000 population or more and these are located in the irrigated sections along the Arkansas and South Platte Rivers. This same sparsity of population is evident in Wyoming and perhaps to a slightly lesser extent in New Mexico.

Figure 2 shows the yearly distribution [2] of tornadoes in the Forecast District for the period 1916–51. There have been 2 years during the past 36 years in which no tornadoes were reported during these months, while the greatest number reported in any year was 11 occurrences in 1923 followed closely by 10 occurrences in 1949 and 9 in 1951.

Figure 3 is a smoothed distribution of tornado occurrences by days designed to bring out the period of maximum occurrence. Tornadoes were tabulated by 5-day

[1] A total of only four tornadoes occurred in the district during the period October through March 1916–51.

[2] The totals of the spatial and yearly distributions differ by one because the place of occurrence of a tornado in September 1941 in Wyoming was not listed.

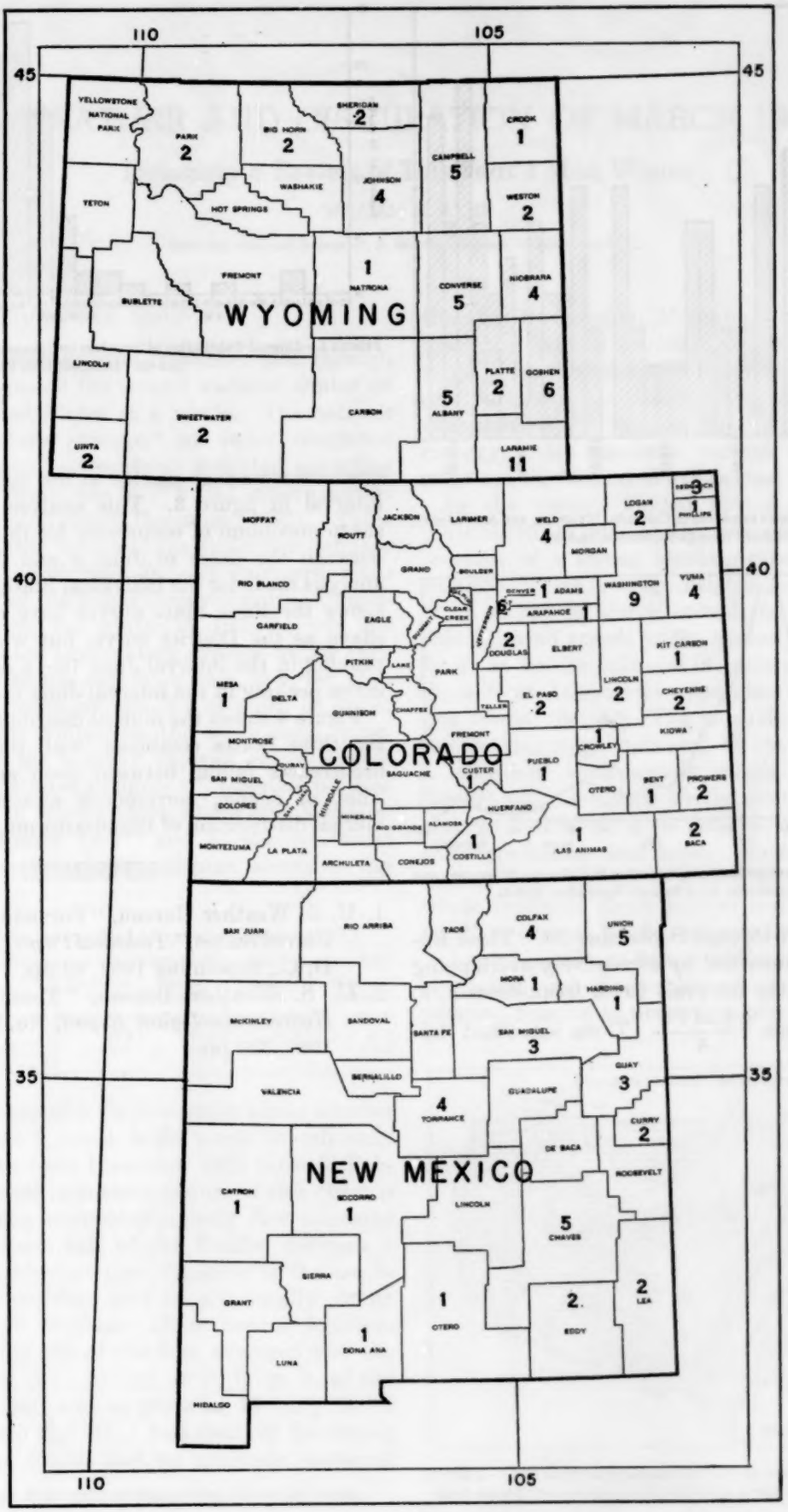

FIGURE 1.—Distribution by counties of tornadoes in Colorado, Wyoming, and New Mexico for the period April through September 1916–51.

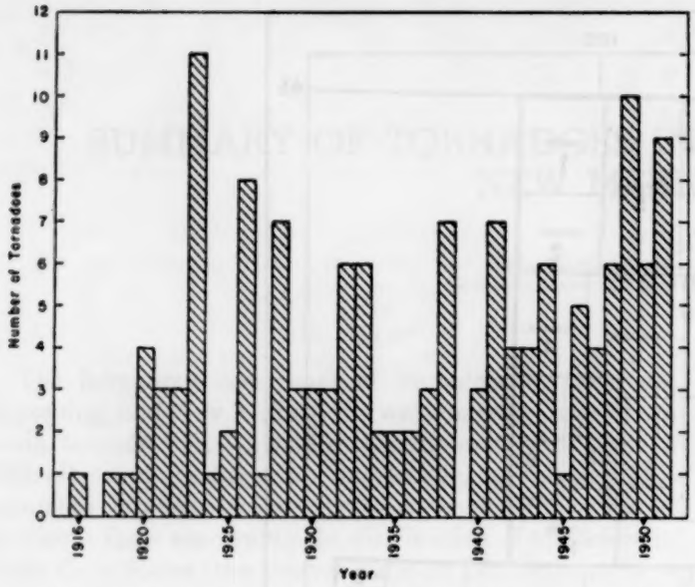

FIGURE 2.—Distribution by years of tornadoes in Colorado, Wyoming, and New Mexico, for the period April through September, 1916–51.

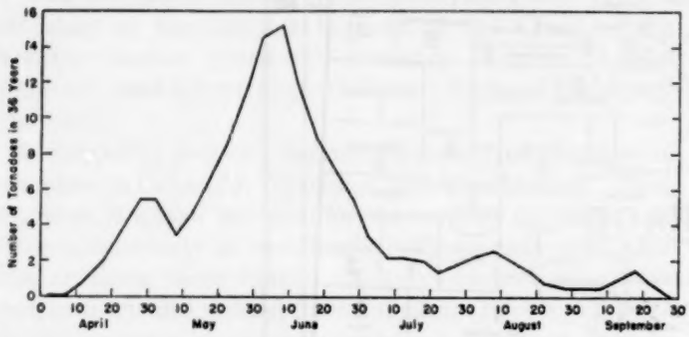

FIGURE 3.—Smoothed frequency distribution of tornadoes in Colorado, Wyoming, and New Mexico for 5-day intervals, April through September, 1916–51.

intervals from April 1 through September 30. These frequencies were then smoothed by successively overlapping three consecutive 5-day intervals (with frequencies a, b, and c) by the formula $\frac{a+2b+c}{4}$. These smoothed frequencies were then plotted at the midpoint of each 5-day interval in figure 3. This analysis brings out a very sharp maximum of occurrence for the District as a whole between the dates of June 5 and June 10. A similar analysis made for the individual States (curves not shown) shows the three State curves have essentially the same shape as the District curve, but with Colorado's curve peaking in the interval June 10–15 and the New Mexico curve peaking in the interval June 1–5.

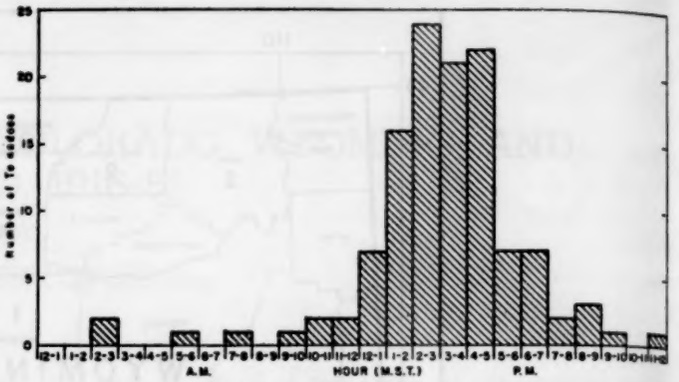

FIGURE 4.—Diurnal distribution of tornadoes in Colorado, Wyoming, and New Mexico, 1916–50. (Adapted from [1].)

Figure 4 shows the diurnal distribution of tornadoes for the three States combined, with the great majority of occurrences falling between noon and 7 P. M., MST. This, of course, corresponds almost exactly with the diurnal distribution of thunderstorms in this region [2].

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THE WEATHER AND CIRCULATION OF MARCH 1953[1]—

Including a Review of This Year's Mild Winter

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THE WINTER SEASON

The three winter months from December 1952 through February 1953 comprised the second warmest winter on record for the United States as a whole. The nation's "weighted temperature average," an index computed from State-wide mean temperatures weighted according to the areas of each State, was 36.7° F., 3.1° above normal for the 60-year period of record (beginning 1893). Table 1 shows that the mildest month of the winter was January [1] which was also the warmest January on record, while the coldest weather of the winter occurred during December [2]. Only during the winter of 1933–34 was the United States weighted temperature average higher than it was this winter. In the 1933–34 winter, however, temperatures averaged below normal (by as much as 8°) in the Northeast. This winter, on the other hand, practically all parts of the country enjoyed above normal temperatures, as illustrated in figure 1. Greatest positive anomalies occurred in the Northern Plains and Northern Rocky Mountain States (+8°) and in the Northeast (+6°), while temperatures averaged near normal in the Southeast.

TABLE 1.—*United States weighted temperature averages (°F.)*

	December 1952	January 1953	February 1953	Winter 1952-53
Temperature	34.9	37.9	37.3	36.7
Departure from 60-year average	+0.6	+5.8	+2.8	+3.1

The circulation responsible for this winter's mild weather is illustrated in figure 2, which is the mean 700-mb. map for the three months from December 1952 through February 1953. The most important feature of this chart is the abnormally strong west-southwesterly flow indicated throughout the eastern half of the Pacific, between a deeper than normal Aleutian Low, displaced to the southeast of its normal position, and an abnormally strong Eastern Pacific High northeast of its normal location. Wind speeds along the axis of this flow, averaged over the entire winter season, were as high as 50 m. p. h. at the 700-mb. level (fig. 3a), and as great as 15 m. p. h. in excess of normal speed (fig. 3b). As a result of this strong "jet stream" in the Pacific and its extension eastward through Washington, Montana, and the Dakotas, vast quantities of mild maritime air were carried in repeated surges from the relatively warm waters of the ocean into most of the United States. The effect of this Pacific air was particularly marked in the western part of the country where abnormal warmth was accompanied by ridge conditions and above normal heights at 700 mb.

In the eastern United States an additional factor contributed to the abnormal warmth. This was the presence of a strong blocking-type ridge in the North Atlantic, where average heights for the season were as much as 330 ft. above normal (fig. 2). Because of this "block" wind speeds in the westerly jet stream normally found at middle latitudes of eastern North America and the western Atlantic were considerably weaker than usual this winter (fig. 3). The anomalous circulation around the blocking ridge, indicated by the dashed lines of figure 2, produced southeasterly winds, relative to normal, throughout the eastern United States. This means that onshore flow of maritime Atlantic air was more frequent and more intense than usual. Since the ocean is normally warmer than the land in winter, the strengthened easterly winds produced above normal temperatures throughout the East (except for the extreme Southeast).

A third significant feature of the seasonal mean 700-mb. circulation was the prevalence of southerly wind components, relative to normal, in practically all of Canada,

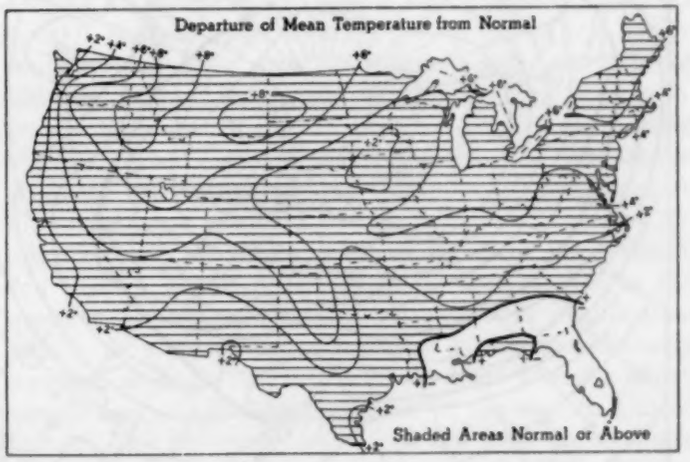

FIGURE 1.—Mean surface temperature anomaly for winter of 1952-53 (Dec.-Feb.). Note above normal temperatures in all parts of the country except the extreme Southeast.

[1] See Charts I-XV following p. 89 for analyzed climatological data for the month.

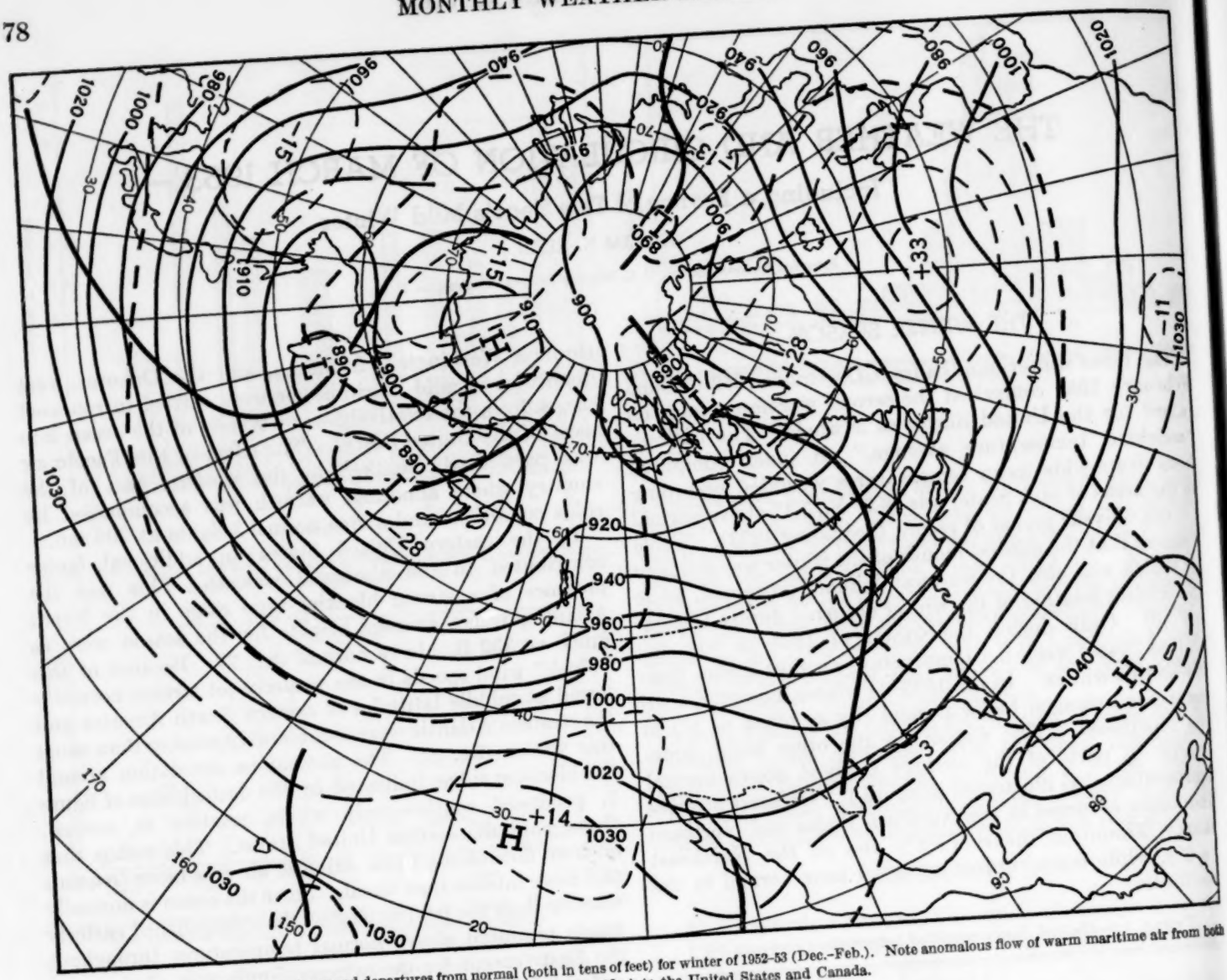

FIGURE 2.—Mean 700-mb. height contours and departures from normal (both in tens of feet) for winter of 1952–53 (Dec.–Feb.). Note anomalous flow of warm maritime air from both the Atlantic and the Pacific into the United States and Canada.

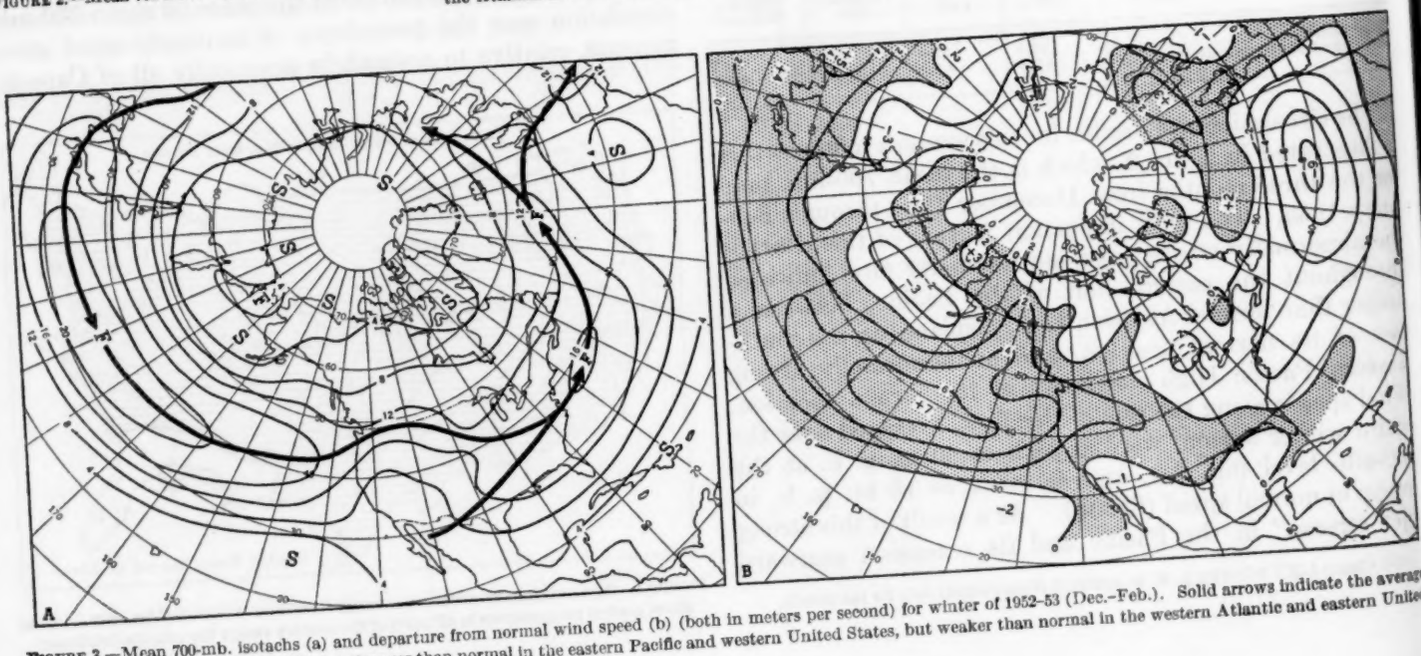

FIGURE 3.—Mean 700-mb. isotachs (a) and departure from normal wind speed (b) (both in meters per second) for winter of 1952–53 (Dec.–Feb.). Solid arrows indicate the average position of the jet stream, which was stronger than normal in the eastern Pacific and western United States, but weaker than normal in the western Atlantic and eastern United States.

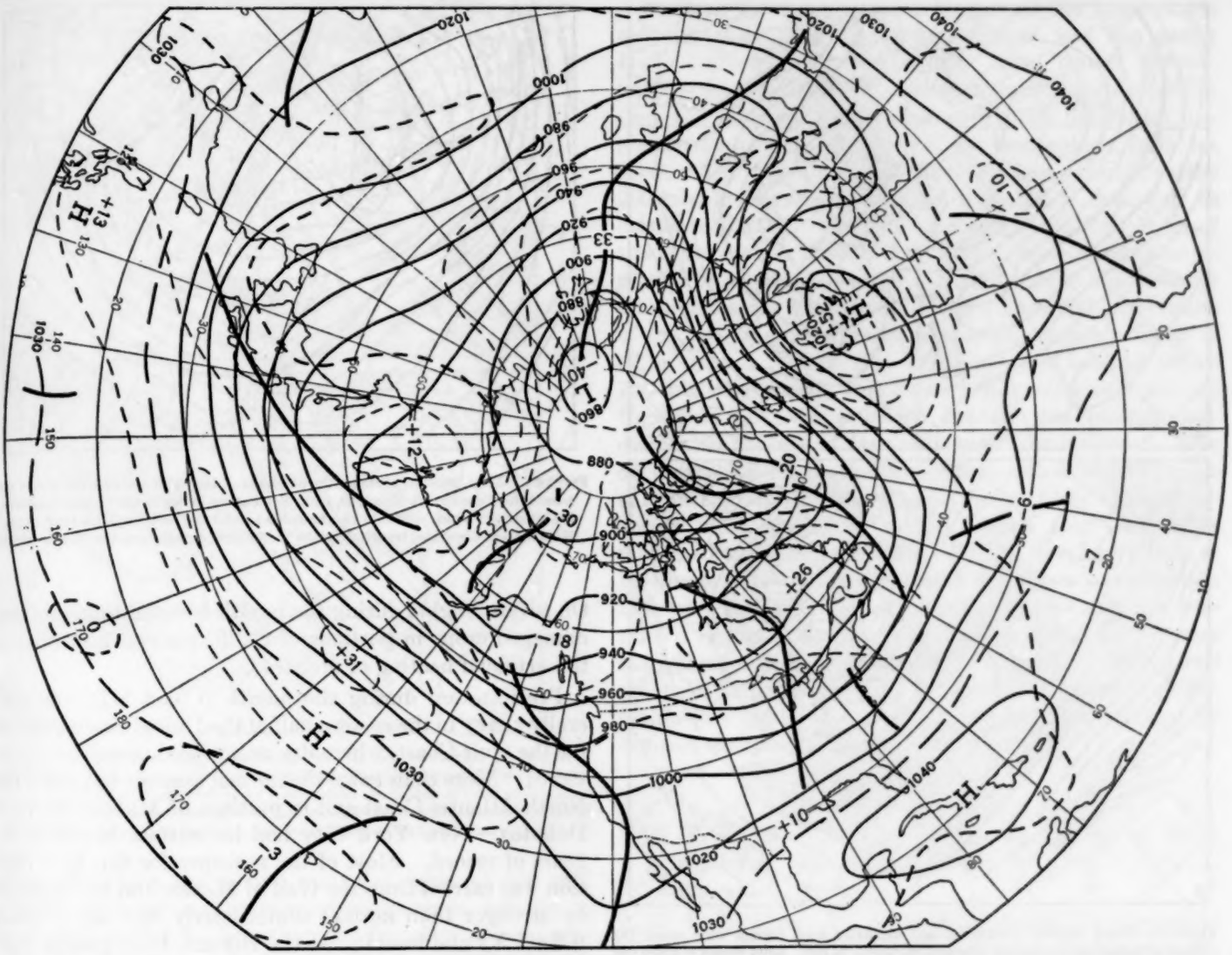

FIGURE 4.—Mean 700-mb. height contours and departures from normal (both in tens of feet) for February 28–March 29, 1953. Note continued anomalous flow of maritime air into Canada and the northern United States.

Alaska, and the Arctic Ocean to the north. This flow produced unusually warm weather throughout this region, the normal source region for cold polar air masses affecting the United States. Consequently, invasions of the United States by cold continental air from Alaska, Canada, and the Arctic were extremely weak, infrequent, and short-lived. Thus, the winter's mild regime may be attributed to the effect of unusual warmth at the polar source as well as the abnormal influx of maritime air from both the Pacific and the Atlantic Oceans.

THE MONTH OF MARCH

The excessive warmth which had characterized the winter season continued to prevail during the month of March in most of the United States (Chart I-B). Continued mild weather was accompanied by persistence of the three circulation features to which the winter warmth may be attributed. In the first place, nearly all of Canada enjoyed southerly wind components, relative to normal, at both 700 mb. (fig. 4) and sea level (Chart XI inset). Secondly, the westerly jet stream in the Pacific continued to blow with exceptional vigor, not only at 700 mb., where wind speeds were as much as 17 m. p. h. greater than normal (fig. 5), but also at the 200-mb. level (fig. 6). The eastward extension of this jet stream produced mild southwesterly wind components, relative to normal, over most of the western United States at 700 mb. Finally, blocking continued to affect the Atlantic and eastern North America, where wind speeds in the westerly jet stream at middle latitudes were weaker than usual. As a result, anomalous flow from a southeasterly direction at both 700 mb. and sea level brought above normal temperatures to nearly all of the eastern United States. It is also noteworthy that few polar anticyclones from Canada were able to penetrate into the United States (fig. 7a and Chart IX), while above normal temperatures

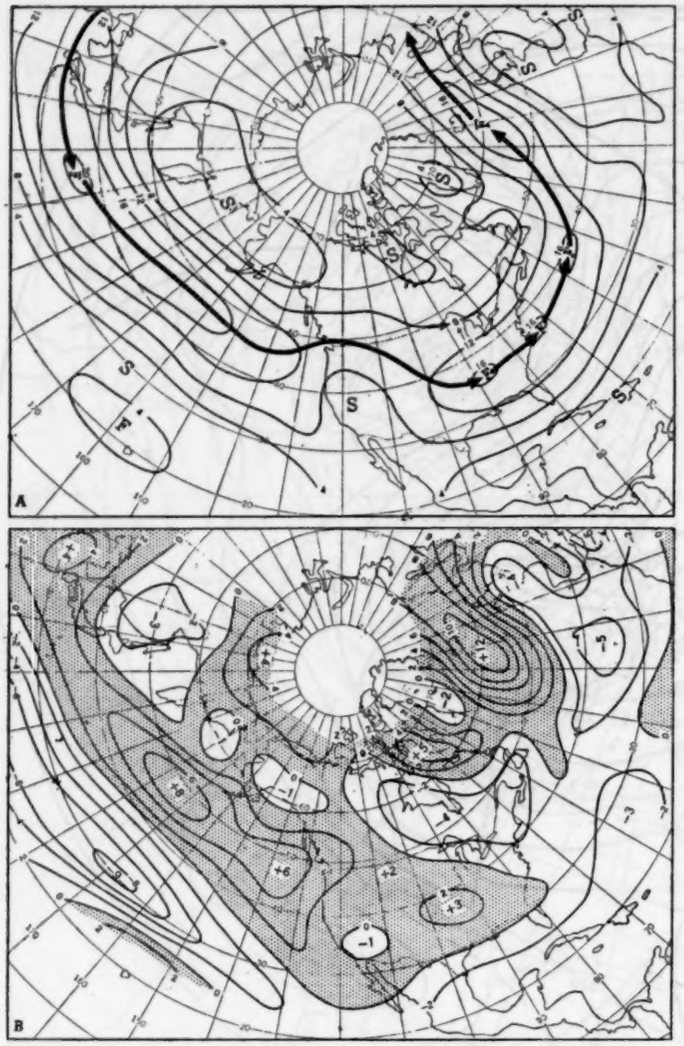

FIGURE 5.—Mean 700-mb. isotachs (a) and departure from normal wind speed (b) (both in meters per second) for February 28–March 29, 1953. Solid arrows indicate the average position of the jet stream, which continued stronger than normal in the eastern Pacific and western United States, but weaker than normal in the western Atlantic and eastern United States.

in most of the country were accompanied by above normal heights at the 700-mb. level (fig. 4). By the end of the month snow cover (Chart V-B) had melted throughout the nation except for mountainous areas, and all ports on the Great Lakes were ice free. Buffalo was completely open to navigation on March 2, the earliest in 100 years.

The only portion of the United States with an appreciable negative temperature anomaly during March was the West Coast area. Here monthly mean temperatures averaged as much as 2° below normal because of the dominance of cool Pacific air masses in stronger than normal northwesterly flow at sea level (Chart XI and inset). Aloft the area was dominated by a deep cold cyclonic circulation, as indicated by the isotherms in Charts XII to XV and by the fact that a contour trough was located along the West Coast at all levels from 700 to 200 mb. During the first week of March many parts of Oregon experienced their coldest weather since November 1952.

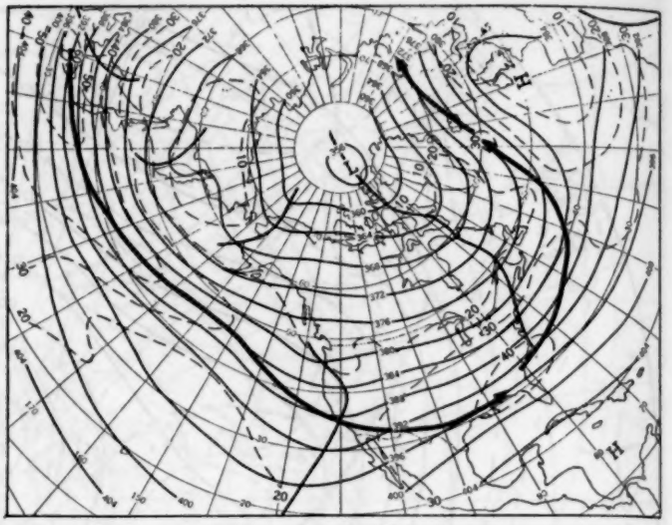

FIGURE 6.—Mean 200-mb. contours (in hundreds of feet) and isotachs (in meters per second) for February 28–March 29, 1953. Solid arrow indicates the average position of the jet stream which split into two branches around the blocking High over Britain. Note the well-developed trough along the West Coast, directly over the 700-mb. trough.

On several nights during the month freezing temperatures damaged crops in portions of California and necessitated the artificial heating of orchards.

Precipitation during the month (Chart III) was generally heavy in the eastern half of the United States, except for the Gulf Coast, where dry anticyclonic conditions prevailed. More than twice the normal amount fell along the North Atlantic Coast and in portions of Missouri and the Dakotas. New York City had its wettest March in 83 years of record. Most of the moisture for this precipitation was carried from the Gulf of Mexico and the Atlantic by stronger than normal southeasterly flow at sea level (Chart XI and inset). At the 700-mb. level greater than normal cyclonic vorticity generally prevailed in the region of heavy precipitation. There was a tendency for this region to be split into an eastern and a western branch, with less precipitation in a band just west of the Appalachian Mountains from Ohio to Alabama. A corresponding split was evident in the cyclone tracks (fig. 7b and Chart X), with one principal track along the Atlantic Coast and the other from Colorado through Michigan. Many of these cyclones were blocked by the strong ridge in eastern Canada and forced to decelerate and recurve sharply to the north and northwest. During the last week of the month a storm of this sort caused 4 to 6 inches of rain along the entire New England coast and serious flood conditions developed in parts of Maine, New Hampshire, and New York.[2] Another such storm was responsible for tornadoes, hail, and high winds in parts of the Mississippi Valley on the 21st and 22d.

In the western half of the United States precipitation was generally subnormal. This area was dominated by

[2] For further details see adjoining article by Lennehan and Holzworth.

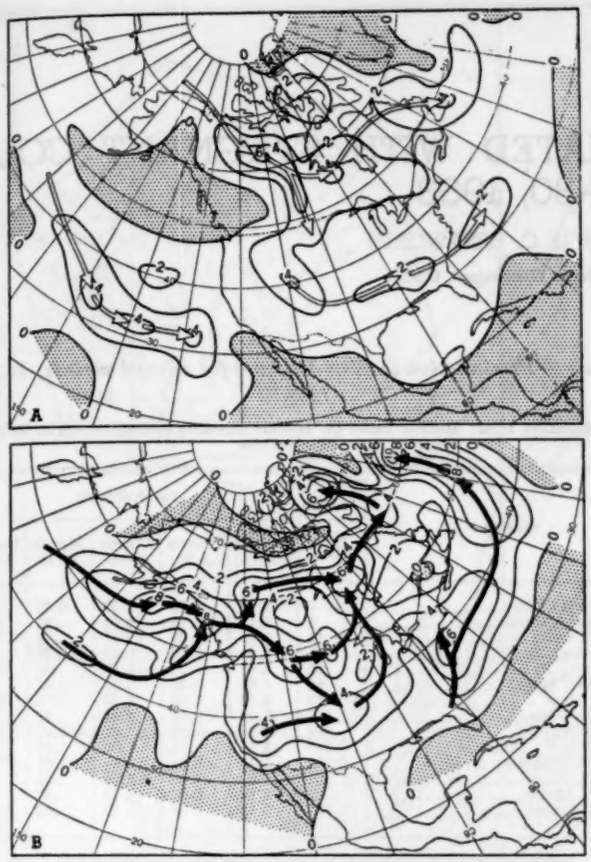

FIGURE 7.—Frequency of anticyclone passages (a) and cyclone passages (b) (within 5° squares at 45° N.) during March 1953. Well-defined anticyclone tracks are indicated by open arrows and cyclone tracks by solid arrows. Note lack of polar anticyclones in the United States, ill-defined cyclone track across North America, and lack of normal cyclonic activity in the St. Lawrence Valley. (All data derived from Charts IX and X.)

ridge conditions and above normal heights at 700 mb. together with dry northerly wind components, relative to normal, at sea level. Less than one-fourth of normal precipitation fell during the month in parts of California, Nevada, Wyoming, and Colorado. State-wide precipitation in Wyoming and Nevada averaged only 40 percent and 43 percent of normal, respectively. Strong winds and blowing dust aggravated the droughty situation in the western Great Plains. California received some relief from last month's severe drought [3] in northern sections, but precipitation continued subnormal in most of the State with the greatest deficiency in the south.

Perhaps the most notable feature of the hemispheric circulation (outside of North America) was the strong High centered over the British Isles, where 700-mb. heights averaged 520 ft. above normal for the month (fig. 4). This High extended with little horizontal displacement through all layers of the troposphere, from sea level, where pressures were 20 mb. above normal, to the 200-mb. level, where a closed circulation was still in existence (fig. 6). This was a classical blocking High of the type recently described by Rex [4] since it was accompanied by a well-marked split or difluence in the westerly jet stream some distance upstream. The northerly branch of the jet stream reached a peak mean monthly speed of 67 m. p. h. at 200 mb. (fig. 6) just south of Iceland, where 700-mb. wind speeds were 27 m. p. h. greater than normal (fig. 5b); but the southern branch was incompletely delineated because of lack of data at low latitudes. The occurrence of this block during the month of March is also a characteristic feature since Atlantic blocking activity occurs more frequently during March than any other month of the year except May [4]. A fortunate result of the predominance of anticyclonic conditions over western Europe was the fact that prevailingly fair weather permitted repair of much of the damage inflicted by severe storminess earlier in the year [1]. In parts of eastern and southern England less than 10 percent of normal precipitation was recorded during March, and new records for dryness were established.

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4. D. F. Rex, "Blocking Action in the Middle Troposphere and Its Effect upon Regional Climate," *Tellus*, vol. 2, Nos. 3 and 4, Aug. and Nov. 1950, pp. 196–211 and 275–301.

CYCLOGENESIS AND FLOODS ASSOCIATED WITH STAGNANT COLD LOW, MARCH 25–30, 1953

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INTRODUCTION

Prior to March 25, 1953 a cold trough aloft moved eastward across the United States and during the next few days was partially responsible for the development of a series of storms along the East Coast. These storms, the result of cyclogenesis associated with the cold Low aloft which broke off from the southern end of the cold trough, deepened to various degrees at sea level and four of them brought heavy rains to New England. Even before these rainstorms, many stations in New England had already received more than normal total rainfall for March. The additional rainfall set several new precipitation records in the area and brought damaging floods along several rivers. The excessive rainfall and consequently the severe floods occurred principally in southern and western Maine.

In the following paragraphs, the rainfall and flooding during the period March 25–30 will be summarized and the synoptic conditions which produced them will be analyzed.

RAINFALL

The geographic distribution of the rainfall over the 7-day period March 25–31 is shown in figure 1 which is based on an analysis of data from 235 stations in New England made by J. K. McGuire and Samuel Penn of the Boston Weather Bureau Office. During the period between the 24th and 28th the centers of heaviest rain in general progressed northeastward along a path stretching from Virginia to northern Maine. The heavy rainfall of the 29th, 30th, and 31st was confined mainly to the coastal area of New England. Vermont and the extreme western portions of Massachusetts and Connecticut received only light rain during these last three stormy days. In Maine all stations south of 46° N. reported 5-day storm rainfall totals which equalled or exceeded the amounts received during the first 23 days of the month. Rumford, Maine received double the amount received in the first 23 days.

These heavy downpours came at the end of a month which had already produced normal or above normal precipitation at most of the stations in New England. Table 1 gives a comparison of rainfall amounts reported at a number of cities in New England for the two parts of the storm period, the first 23 days of the month, and for the entire month. The normal March precipitation is also given for stations where available. The periods for which rainfall was totalled are not all the same in table 1 since the published station data are the amounts for calendar days whereas our charts and material are for the 24-hour periods ending at 0730 EST. Many of the stations in New England reported record-breaking precipitation for the month of March. New Haven, Conn., with 10.78 in., had the greatest amount in its 81 years of record. Boston broke an 82-year record and reported the highest total for any month there since July 1921. The total of 11.69 in. is 7.57 in. more than Boston's normal for March. The 24-hour total of 3.09 in. for the period ending at 1900 EST, March 30 is 0.05 in. greater than any previous 24-hour total in March. The previous record was set on March 26–27, 1877. March precipitation records were broken also at Hartford, Conn., Pittsfield and Blue Hill, Mass., and Portland, Maine.

It is of interest to compare the observed rainfall with amounts computed from an analysis of the air flow in the vicinity of New England. These computations were

TABLE 1.—*Precipitation in New England for selected periods, March 1953*

A. Precipitation totals (inches) based on 24-hour amounts ending midnight EST, at first order stations

Station	Ground elevation (ft.)	Precipitation				
		Monthly normal	March 1–23	March 24–29	March 30–31	March 1–31
Bridgeport, Conn.	7	3.60	6.52	2.23	0.65	9.40
New Haven, Conn.	6	4.12	7.18	2.95	.65	10.78
Hartford, Conn.	15	3.53	5.90	2.37	.94	9.21
Block Island, R. I.	33	3.54	4.78	1.45	.29	6.52
Providence, R. I.	55	3.58	5.78	1.48	.66	7.92
Nantucket, Mass.	43	4.05	3.33	2.32	.57	6.22
Boston, Mass.	15	3.43	5.89	2.29	2.82	11.00
Pittsfield, Mass.	1,153	3.22	3.69	2.53	.61	6.83
Concord, N. H.	289	3.04	4.48	2.21	1.12	7.71
Burlington, Vt.	340	2.19	.96	1.09	.98	3.03
Mount Washington, N. H.	6,262	5.55	2.04	3.44	1.91	7.39
Portland, Maine	61	4.03	5.49	3.55	.93	9.97
Eastport, Maine	33	2.88	2.83	4.19	.40	7.42
Caribou, Maine	628	2.40	2.51	1.82	.80	5.13

B. Precipitation totals (inches) based on 24-hour amounts ending 0730 EST

Worcester, Mass.	460	4.08	4.86	3.28	0.35	8.49
Lebanon, N. H.	570		2.38	2.46	.24	5.08
Rumford, Maine	674	3.44	3.23	7.22	.98	11.43
Augusta, Maine	353		3.42	5.42	.33	9.17
Old Town, Maine	162	3.01	2.39	3.02	.32	5.73
Houlton, Maine	476	2.75	2.92	2.42	.84	6.12

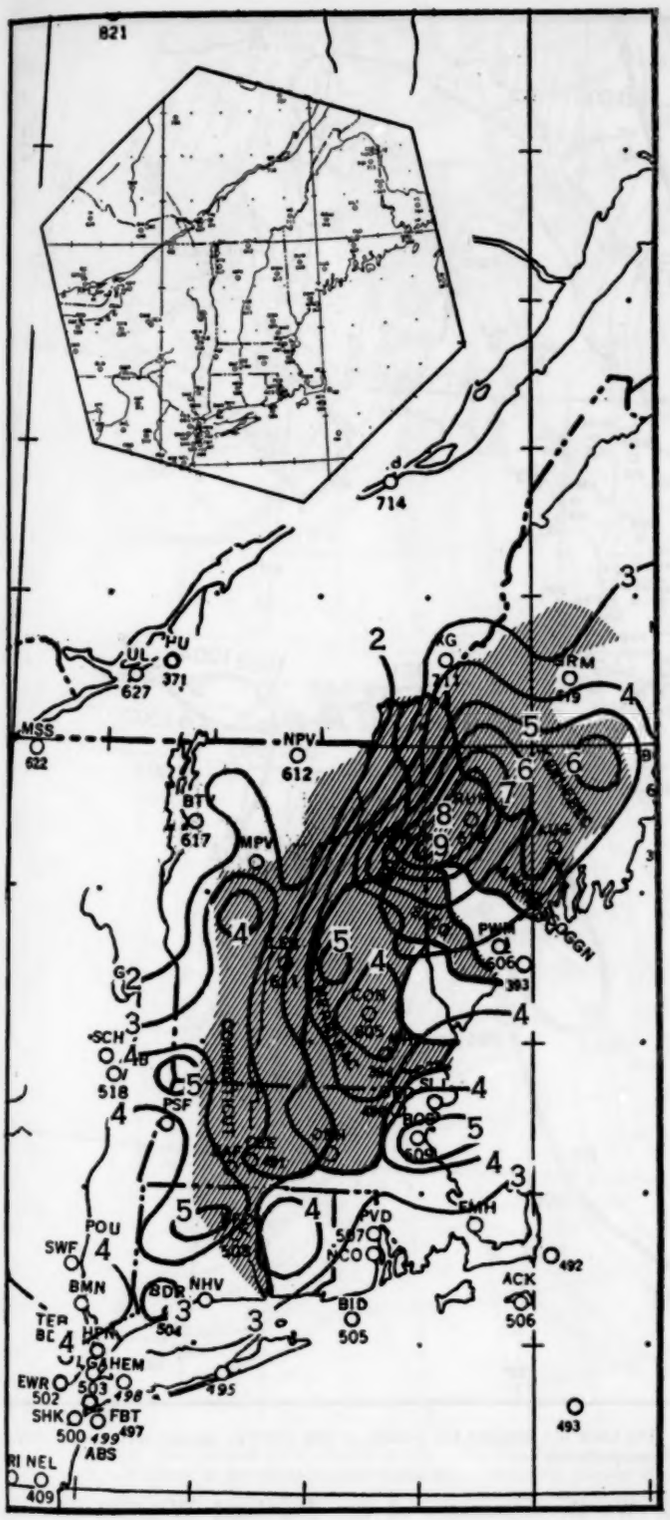

FIGURE 1.—Isohyetal map (in inches) for March 24-31, 1953, based on 24-hour rainfall amounts measured at 0730 EST. River basins are shaded and outlined. The hexagon inset outlines the area of the six triangles used in the Bellamy method to compute convergence. (See tables 1 and 2.)

made in collaboration with P. M. Kuhn of the Weather Bureau's Short Range Forecast Development Section. Kuhn [1] in connection with the work of Thompson and Collins [2], has adapted Bellamy's [3] method for computing vertical velocities to a more elaborate procedure to compute precipitation amounts. The area enclosed by the six triangles used in the Bellamy method to compute the convergence is shown in the inset in figure 1. The results of the computations are shown in table 2. Although the vertical velocities were not sufficient to account for the excessive precipitation reported at Rumford, Maine for the 24-hour period ending at 0730 EST on the 27th, they were sufficient to account for the average amount for the entire area for that period.

TABLE 2.—*Computed divergence, D, vertical velocity, W, and precipitation. Subscripts to D and W indicate pressure surfaces to which data pertain*

March (GMT)	Divergence (10^{-6} sec.$^{-1}$)					Vertical velocity (cm. sec.$^{-1}$)						12-hour precipitation (in.)
	D_{850}	D_{800}	D_{700}	D_{600}	D_{500}	$W_{s/c}$	W_{850}	W_{800}	W_{700}	W_{600}	W_{500}	
26, 1500	−1.8	−2.3	−2.0	−2.1	−0.2	3.0	3.9	6.3	11.0	20.1	35.6	0.86
27, 0300	−1.6	−1.0	−.7	−.5	−1.1	3.0	3.8	5.3	7.6	12.2	21.7	
27, 1500	−2.4	−.1	−2.0	−.4	−2.0	2.0	3.2	4.6	6.9	13.0	24.0	1.10

FLOODS

The base map in figure 1 includes outlines of the basins of the rivers which were affected by floods and shows that the maximum rainfall during this period covered the upper portions of the Saco and Androscoggin Rivers in New Hampshire and Maine; Rumford, Maine, which received 8.20 in. of rain from March 25–April 1, is on the upper portion of the Androscoggin. The flood was of record proportions in the Saco and Androscoggin but their smaller tributary streams were in relatively greater flood. The Kennebec, the Merrimack, and the Connecticut Rivers were also in flood during the period. The recorded flow data for some of the rivers are given in figure 2, the curves of which are based upon data sent by E. W. G. Kliemann of the Weather Bureau Office, Portland, Maine.

The flooding in Maine was comparable to the March 1936 flood during which 5 persons lost their lives, 25 million dollars in property was lost, 125 bridges were

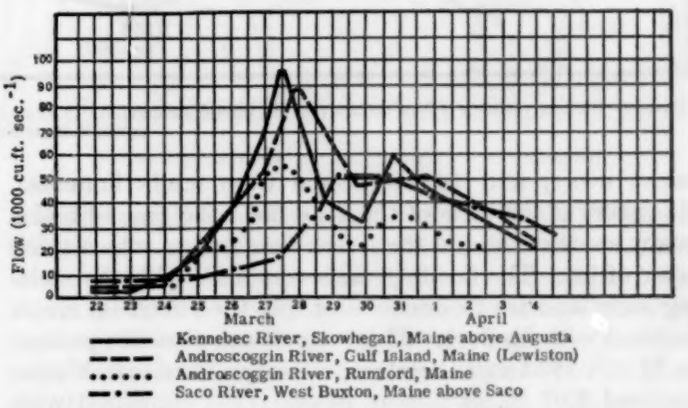

FIGURE 2.—Stream flow for March 22 to April 4, 1953.

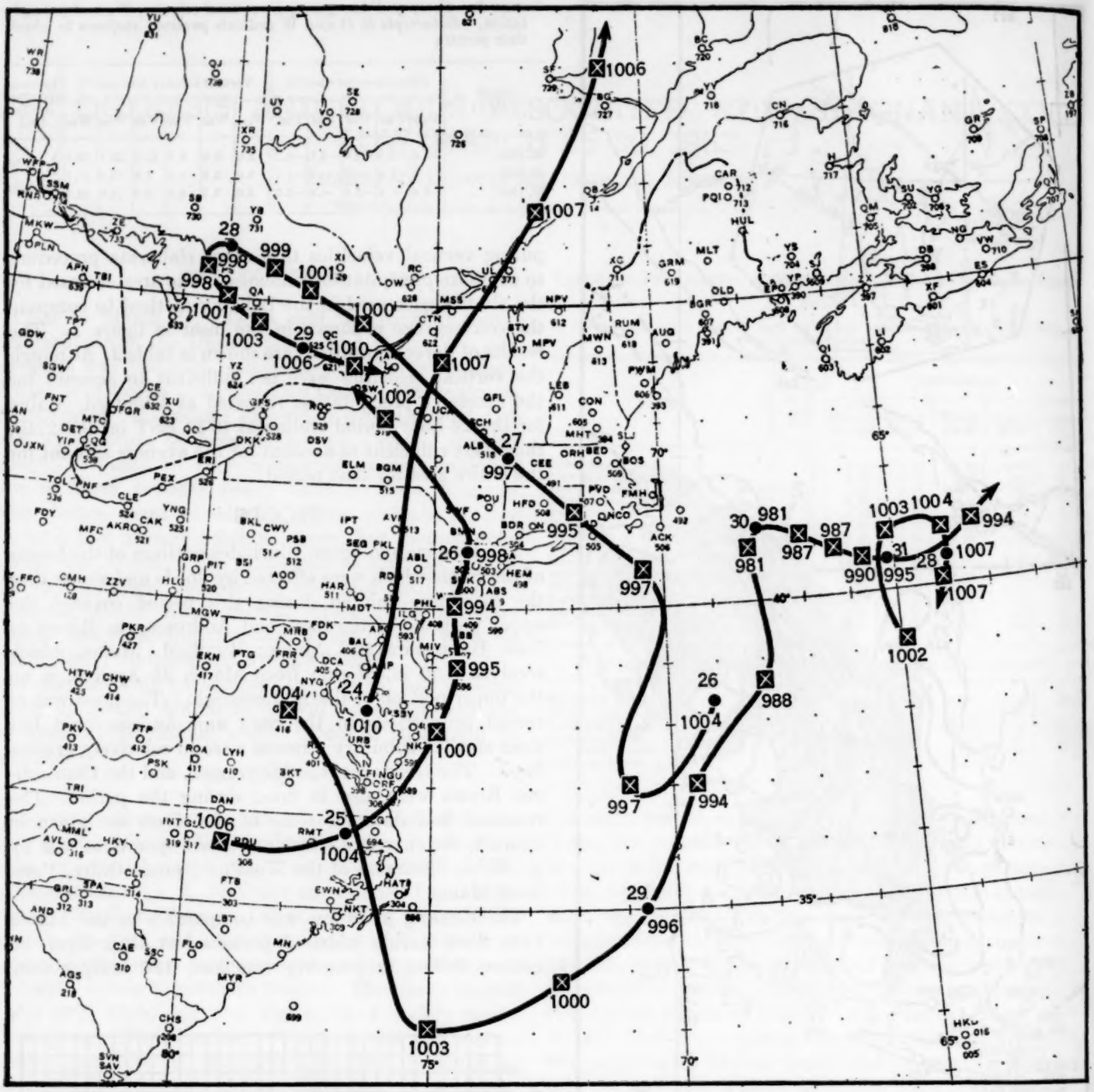

FIGURE 3.—Six-hour positions of Low centers with the central pressure, March 24–31, 1953. The black dot indicates the position at 1230 GMT for the day of the month shown; crosses indicate intermediate positions.

swept away, and 10,000 people were made homeless. However, at the time of the 1936 flood the ground had a heavy snow cover and the rivers were frozen with a thick layer of ice. The flooding rains combined with the melting snow and ice to double or triple the runoff on rivers jammed with ice floes. These conditions were not present in March 1953 and therefore, although Portland, Maine, received 9.97 in. of rain in March 1953 compared with 7.48 in. in March 1936, the floods were not so severe. The following report, quoted in part, was received from E. W. G. Kliemann of the Portland Weather Bureau Office: "The State estimated that $500,000 damage was caused to State roads and bridges and an equal amount to town-owned roads and bridges. And it is estimated that $9,000,000 damage was caused, mostly by silt and by work stoppage and ruined furniture. The total estimate of flood damage is therefore $10,000,000. . . . The major rivers did not approach the stages reached during the record flood of 1936 but several of the smaller rivers exceeded their previous records."

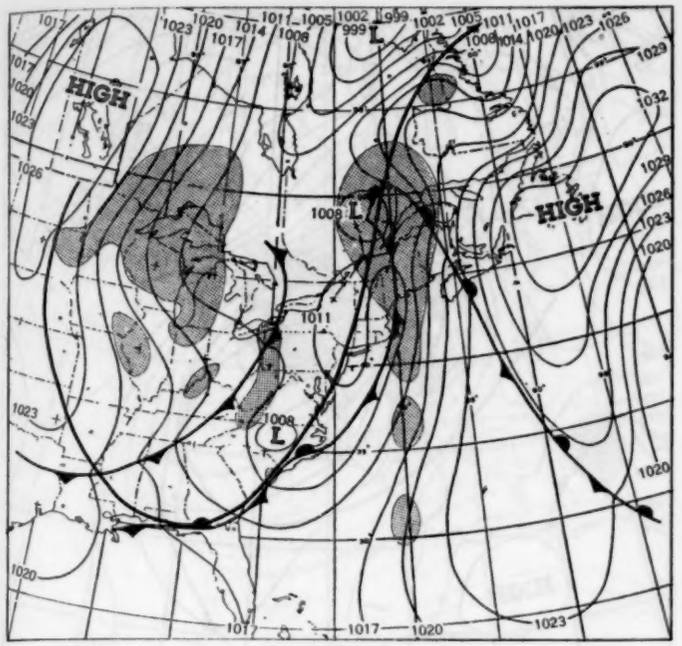

FIGURE 4.—Surface weather chart for 0630 GMT, March 25, 1953. Shading indicates areas of active precipitation. Small "x's" indicate the past positions of the Low at 6-hour intervals. The heavy curved arrow is the axis of the jet stream at 300 mb.

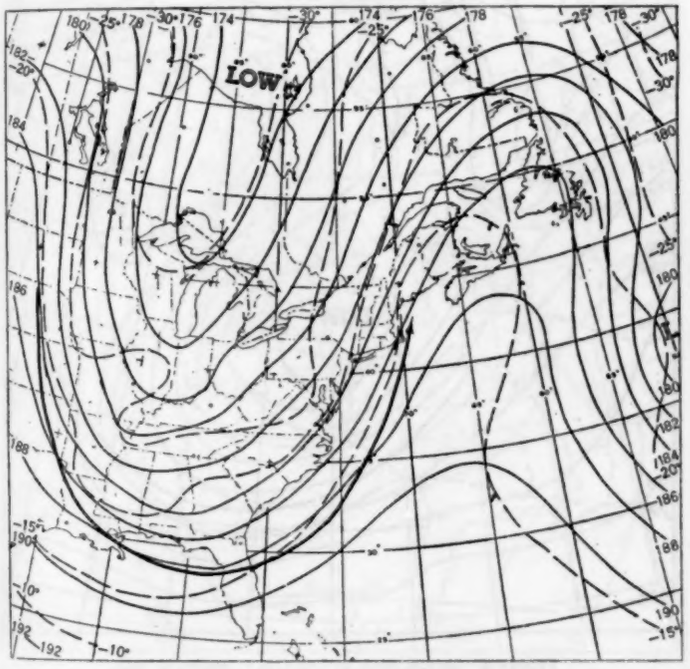

FIGURE 5.—500-mb. chart for 0300 GMT, March 25, 1953. Contours (solid lines) at 200-ft. intervals are labeled in hundreds of geopotential feet. Isotherms (dashed lines) are in intervals of 5° C. The heavy curved line is a constant absolute vorticity trajectory.

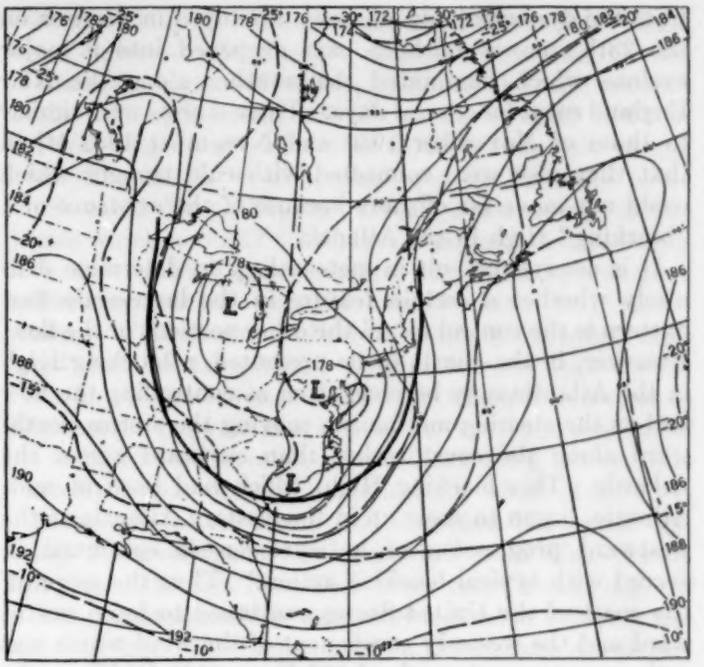

FIGURE 6.—500-mb. chart for 0300 GMT, March 26, 1953.

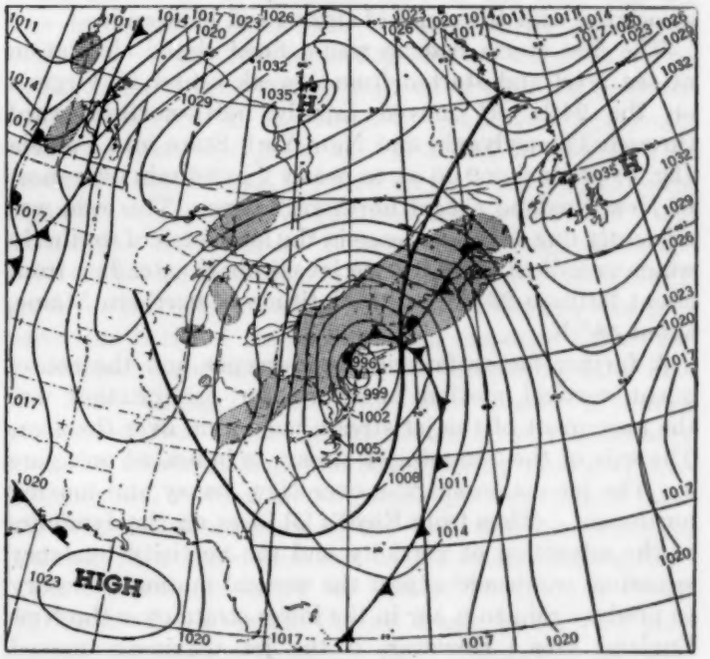

FIGURE 7.—Surface weather chart for 0630 GMT, March 26, 1953.

SYNOPTIC ANALYSIS OF THE CYCLONES

The tracks and central pressures of the storms that brought the excessive rainfall to New England are shown in figure 3. The first storm of the series had a poorly defined center but produced rain in New England on March 24–25. The second storm, which developed in North Carolina early on the 25th, moved up the coast and then northwestward into New York State, producing additional rain in New England on the 25–26th. A third center developed offshore about 200 miles south of Nantucket on the 26th and moved northwestward through southern New England; as it passed through, the heaviest rains for a 24-hour period were reported at 0730 EST on the 27th in New Hampshire and Maine. Still another storm, in some respects the most interesting of the series

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from the dynamic point of view, developed in Virginia on the 28th, moved offshore, and deepened into a major cyclone which dominated the weather along the New England coast for several days. These storms were similar to those of November 1950 and November 1952 [4] in that they also were connected with cold troughs which could not move far offshore because of the existence of a "blocking" High in the Atlantic.

It is always difficult in meteorology to determine definitely whether a certain feature in the large-scale flow pattern is the control for all the other portions of the flow. However, in the charts to be presented, a blocking High in the Atlantic may be recognized as controlling the flow and as the steering mechanism moving the storms northward along the coast rather than eastward across the Atlantic. This blocking High, which had been in mid-Atlantic, began to show up in the western Atlantic as the westward progression of anticyclogenesis continued in accord with typical blocking action.[1] Thus the ridge off the coast of the United States continued to build northward and the westerly component of the wind which was rather pronounced north of 50° N. at 0300 GMT on the 25th (figs. 4 and 5) became progressively weaker on the succeeding charts. With this general picture in mind, some more specific details of the synoptic developments associated with the series of storms will be examined.

The first storm had no well-defined closed circulation at sea level and started from a weak center in Virginia on the 24th. It moved rapidly north-northeastward through Pennsylvania and New York State into Canada (fig. 4) producing 0.50 in. to nearly 2 in. of rain over most of New England except northern Maine. This rain was evidently due to convergence in the long fetch of southerly winds as indicated by the sea level isobars extending from about latitude 25° N. to the latitude of northern Maine, about 48° N.

A further factor favoring convergence and the consequent vertical motion necessary for precipitation was the movement of the jet stream maximum over the area. The axis of the 300-mb. jet stream is indicated on figure 4. The jet maximum was over New Jersey and moving northward. Thus from Riehl's [5] ideas on the dynamics of the advection of vorticity and the vorticity tendency equation, one would expect the vertical motion necessary to produce rain to occur in the lower strata over the New England area. However, if the jet maximum moved along the axis of the jet as shown in the analysis, it would be too far west to conform to theory. At this time the cold trough aloft (fig. 5) was pushing eastward with the cold air advection over New England coming from the southwest with 40-knot winds; consequently the trend was for the jet to be displaced eastward. A displacement of only 100 miles in 12 to 18 hours would have been sufficient for the jet stream and its maximum to be in position to take part in the rain-producing mechanism. This easily could have occurred, for the speed of the trough was actually about 17 knots.

The southern part of the cold trough as shown on the 500-mb. chart for 0300 GMT on the 25th (fig. 5) broke off into a cold Low by 0300 GMT on the 26th (fig. 6). This cold Low continued to dominate the developments in the northeastern United States for at least the next six days.

[1] See discussion of blocking and references cited by Sanders in the article on pp. 67–74.

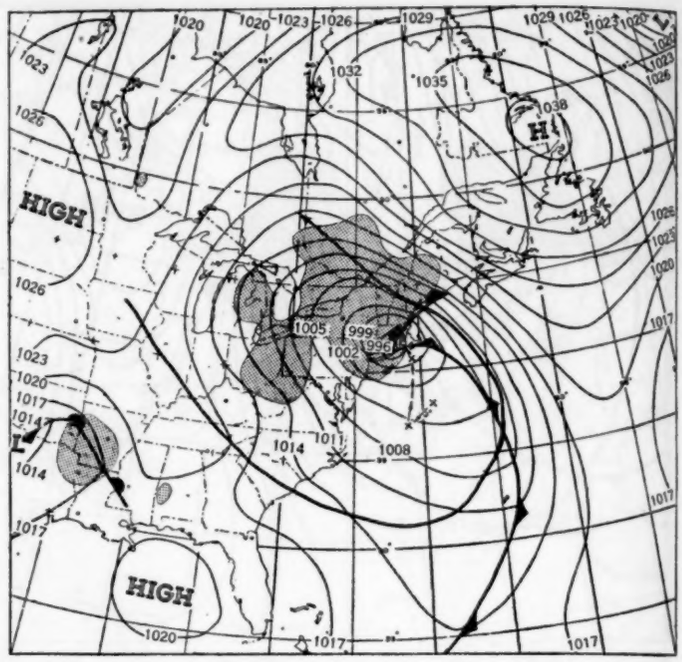

FIGURE 8.—Surface weather chart for 0630 GMT, March 27, 1953.

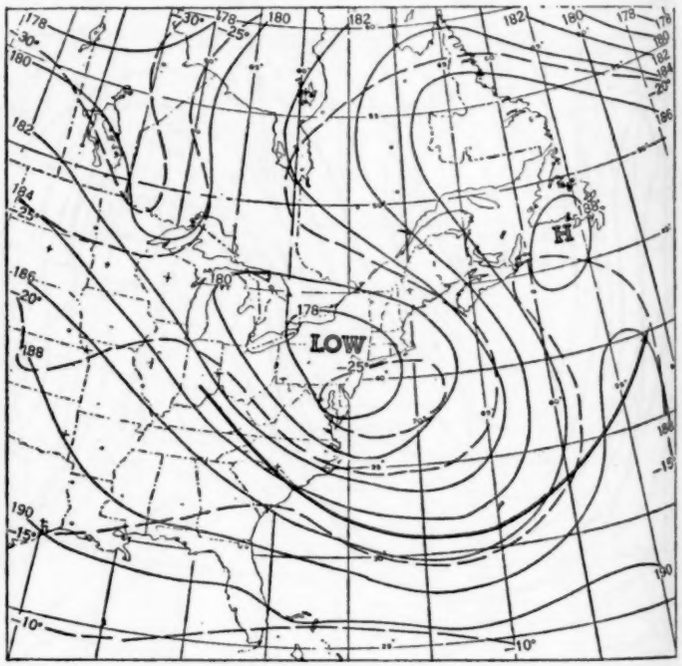

FIGURE 9.—500-mb. chart for 1500 GMT, March 27, 1953.

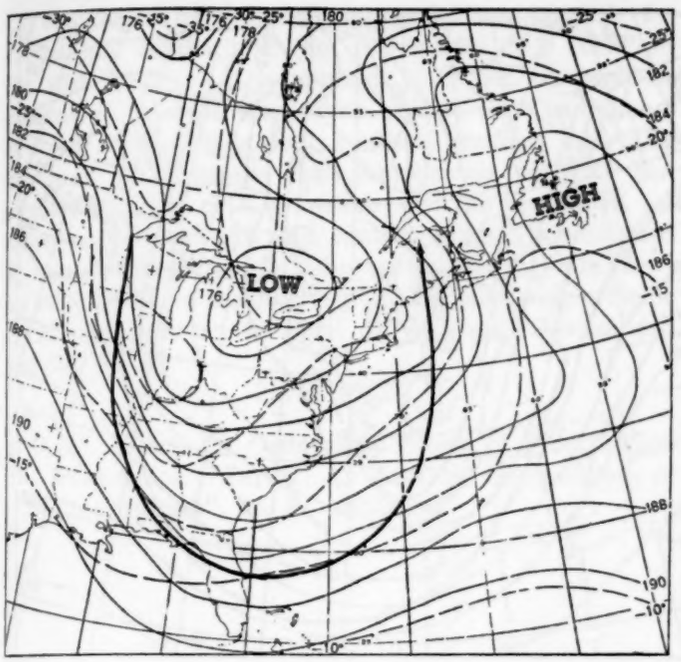

FIGURE 10.—500-mb. chart for 1500 GMT, March 28, 1953.

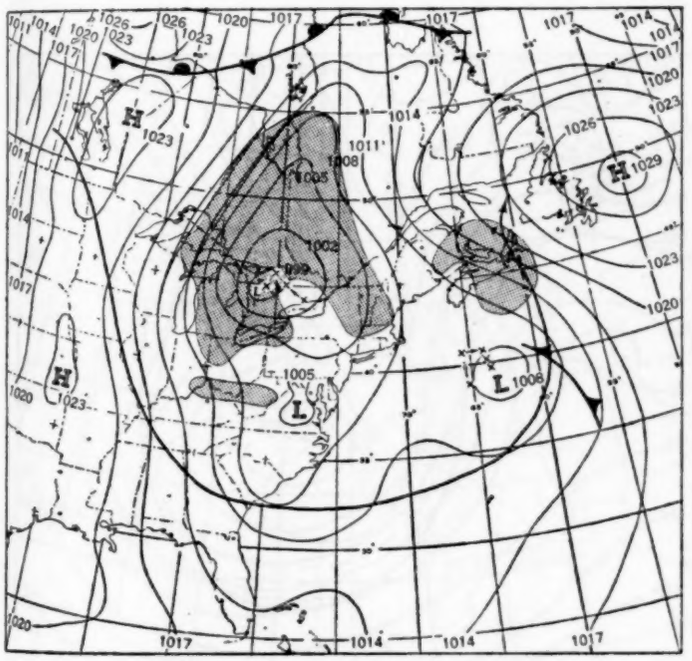

FIGURE 11.—Surface weather chart for 1830 GMT, March 28, 1953.

The Low centered over New Jersey at 0630 GMT on the 26th (fig. 7), the second of the series, had deepened 13 mb. in 24 hours to a central pressure of 994 mb. This is reflected in the obvious increase in gradient at 500 mb. in the southern portion of the trough (fig. 6). The curvature of the field of flow at 500 mb. had not increased noticeably in this region but the shear had increased with the increase in gradient; that is, the cyclonic vorticity had increased. The prognostic charts of the advection (extrapolation) of the constant-absolute-vorticity field, based on barotropic concepts, did not indicate an increase of this magnitude. However, by noting the temperature-height solenoids on the 500-mb. chart for 0300 GMT of the 25th (fig. 5) the advection of the minor cold trough from the vicinity of Memphis to near Hatteras in 24 hours could be anticipated although deepening to the degree which actually took place was unexpected. Thus both the vorticity approach and the direct approach of height-temperature solenoid consideration had shortcomings. The constant-absolute-vorticity trajectory indicated that the trough line would not move appreciably. Thus any advection into the trough which would tend to increase the contour gradient in the southern portion of the trough would have the effect of increasing the cyclonic vorticity in this region of maximum curvature of the flow.

After this second storm had deepened the center followed a curved path northwestward from New Jersey and passed through New York State into Canada (fig. 3). It was this storm which was instrumental in bringing the moist air into New England, but a third storm developed offshore about 1230 GMT on the 26th and produced important effects.

Storm number three moved into New England near Block Island about midnight EST of the 26th (fig. 8). The heavy rains in southern Maine occurred between 0730 EST on the 26th and 0730 EST on the 27th. The cyclogenesis was apparently associated with the dynamic factors inherent in the 300-mb. jet stream maximum which was over Georgia at 0300 GMT on the 26th. This maximum was difficult to follow on the analyses but could logically be expected to progress around the Low; this inference is borne out by the report at 300 mb. of an 85-knot wind from the southeast at Nantucket at 1500 GMT on the 27th. The previous cyclonic circulation had prepared the fields of temperature and moisture before the development and movement of the deepening Low into the New England area. This third center produced accelerated flow of the moist air as it moved onshore toward a stubborn High and consequently produced convergence and vertical motion which gave the record rainfall over the upper parts of the Saco and Androscoggin basins in New Hampshire and Maine as described earlier.

On the 500-mb. chart for March 27 at 1500 GMT (fig. 9) the flow over the Central States had a very pronounced component from the west. However, the flow 24 hours later, March 28 at 1500 GMT (fig. 10), had veered with more pronounced northerly components, and the speeds had increased from approximately 40 knots on the average to over 60 knots. This veering of the flow and increasing speed were significant factors in the cold advection into the western portion of the trough which in turn was followed by an increase in the gradients of temperature and of height at 500 mb. in the southern portion of the trough. This of course implies that the trough deepened somewhat in the southern portion also.

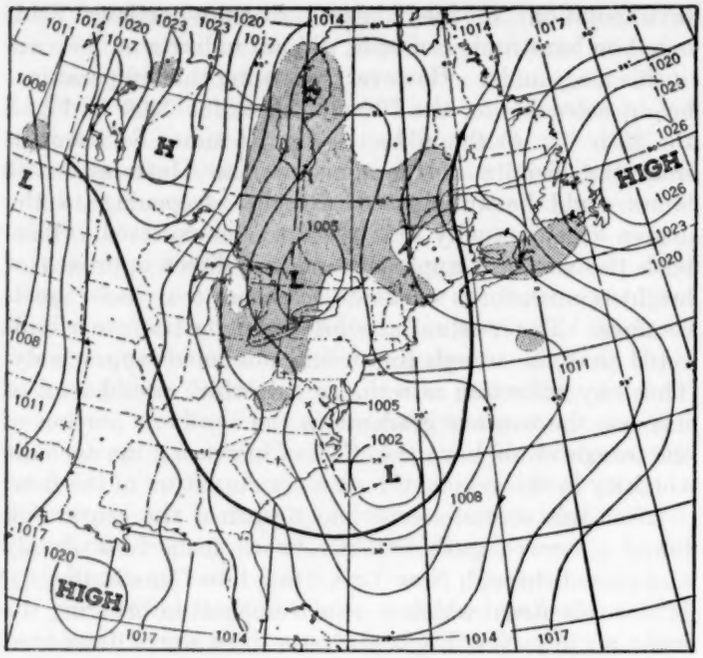

FIGURE 12.—Surface weather chart for 0630 GMT, March 29, 1953.

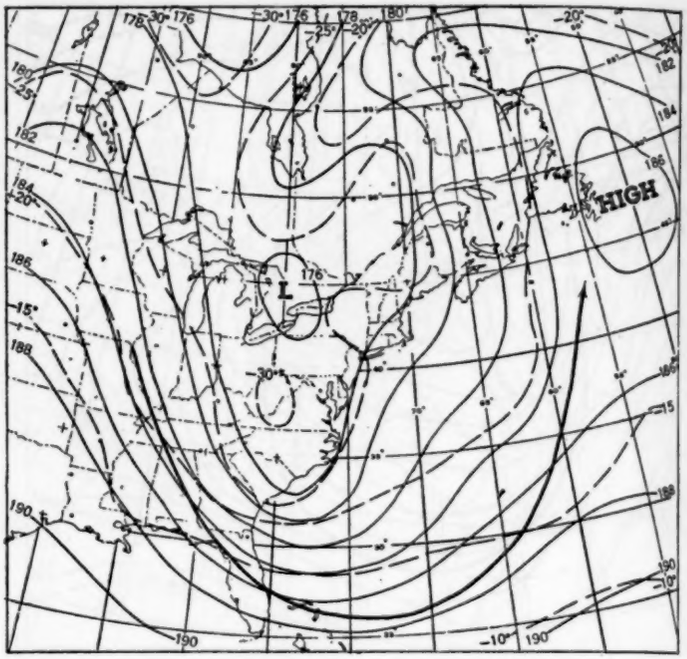

FIGURE 14.—500-mb. chart for 0300 GMT, March 29, 1953.

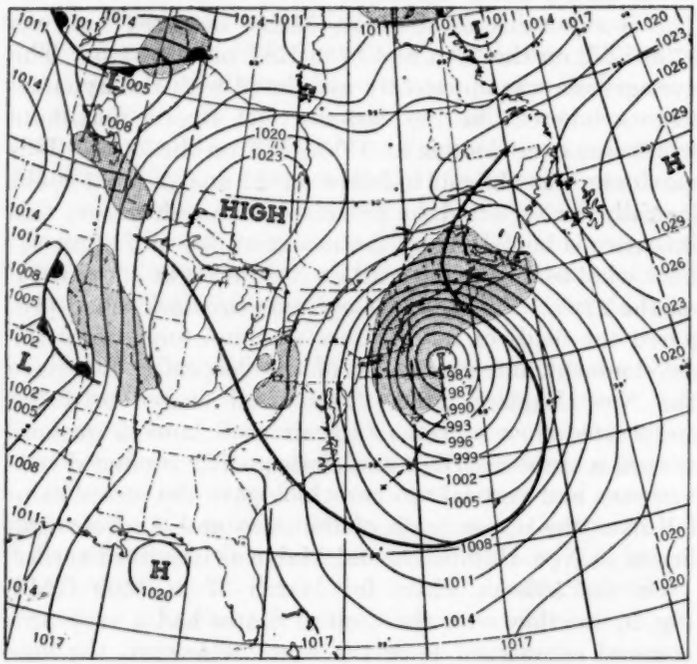

FIGURE 13.—Surface weather chart for 0630 GMT, March 30, 1953.

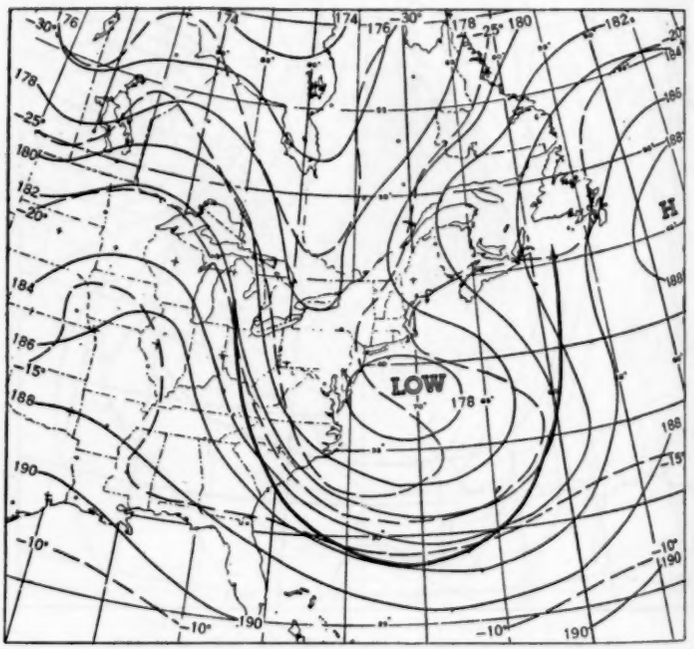

FIGURE 15.—500-mb. chart for 0300 GMT, March 30, 1953.

It is difficult to say in a particular case which phenomenon was the first to appear; or in other words to predicate a definite causal relationship between two observational facts. However, this phenomenon could be anticipated from the 500-mb. chart for 1500 GMT, March 27, for the cold advection indicated by the flow from North Dakota southeastward to the South Atlantic States indicated an increase in gradient and a deepening of the trough in the vicinity of the coast. However, here again, although the trend could be predicted, the degree of the development was not foreseen.

The sea level chart for 1830 GMT of the 28th (fig. 11) shows that a Low center had already formed in Virginia. The cyclogenesis continued for the next 24 hours as the center moved southeastward offshore (fig. 12) and then curved northward with continued deepening (fig. 13).

On comparison of the temperature fields at 500 mb. for 1500 GMT on the 28th (fig. 10) and for 0300 GMT on the 29th (fig. 14) it is apparent that the temperature gradient in the southern portion of the trough had almost doubled. The winds and contour gradient had also increased which means that the cyclonic vorticity had increased. This cold advection with its associated increase in temperature and contour gradients continued to move offshore and is indicated on the 500-mb. chart for 0300 GMT on the 30th (fig. 15) by the strong cyclonic circulation between 30° and 35° N. and between 60° and 65° W.

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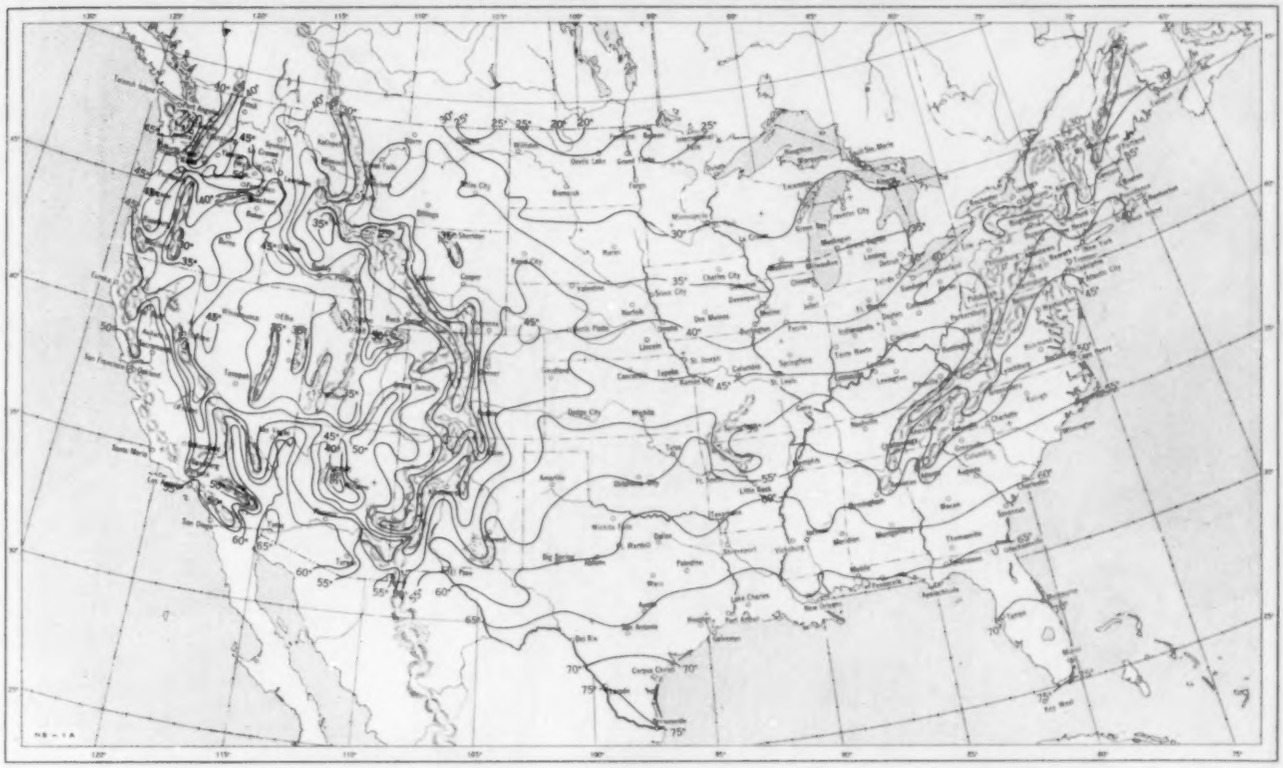
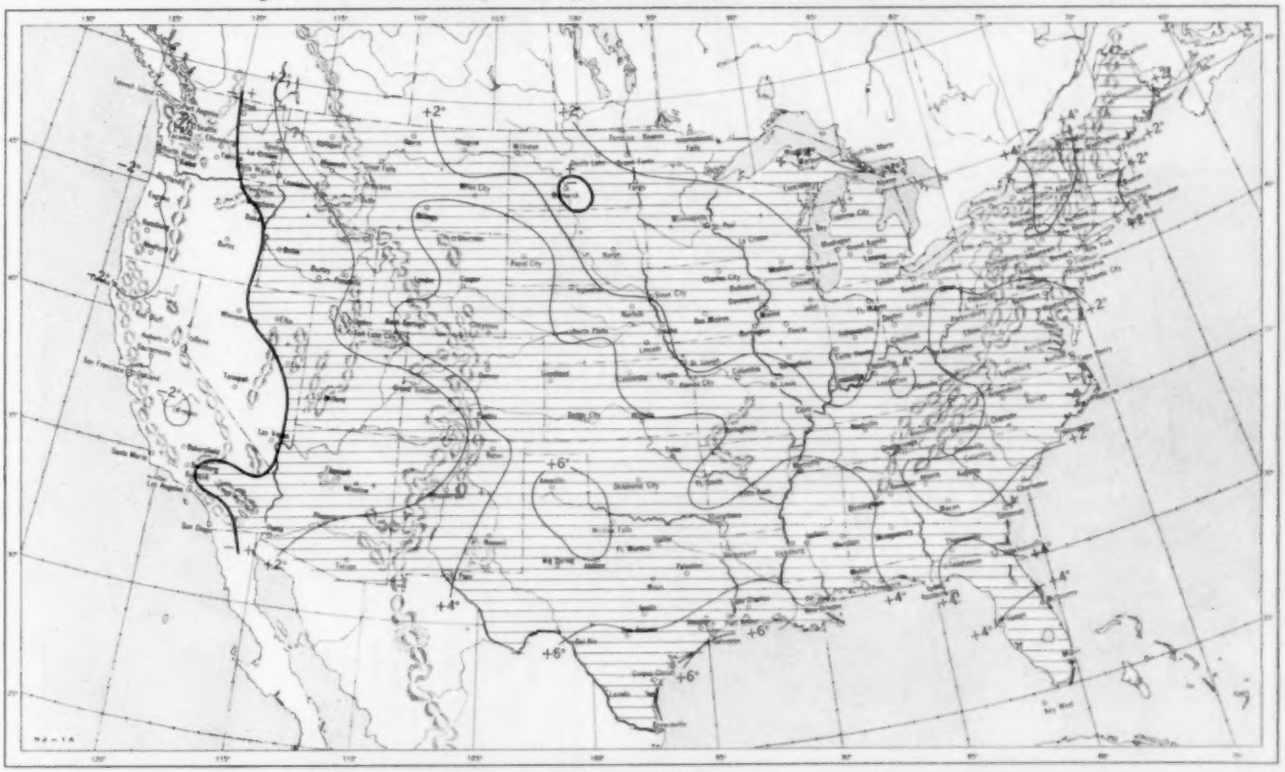
1. P. M. Kuhn, "A Generalized Study of Precipitation Forecasting. Part 2: An Analytic Computation of Precipitation", (to be published).
2. J. C. Thompson and G. O. Collins, "A Generalized Study of Precipitation Forecasting. Part 1: Computation of Precipitation from Fields of Moisture and Wind", *Monthly Weather Review*, vol. 81, No. 4, April 1953, (to be published).
3. John C. Bellamy, "Objective Calculations of Divergence, Vertical Velocity, and Vorticity," *Bulletin of the American Meteorological Society*, vol. 30, No. 2, February 1949, pp. 45–49.
4. C. D. Smith, Jr., and Charlotte L. Roe, "Comparisons between the Storms of November 20–22, 1952 and November 25–27, 1950," *Monthly Weather Review*, vol. 80, No. 11, Nov. 1952, pp. 227–231.
5. Herbert Riehl et al., "Forecasting in Middle Latitudes," *Meteorological Monographs*, vol. 1, No. 5, American Meteorological Society, Boston, June 1952.

Chart I. A. Average Temperature (°F.) at Surface, March 1953.

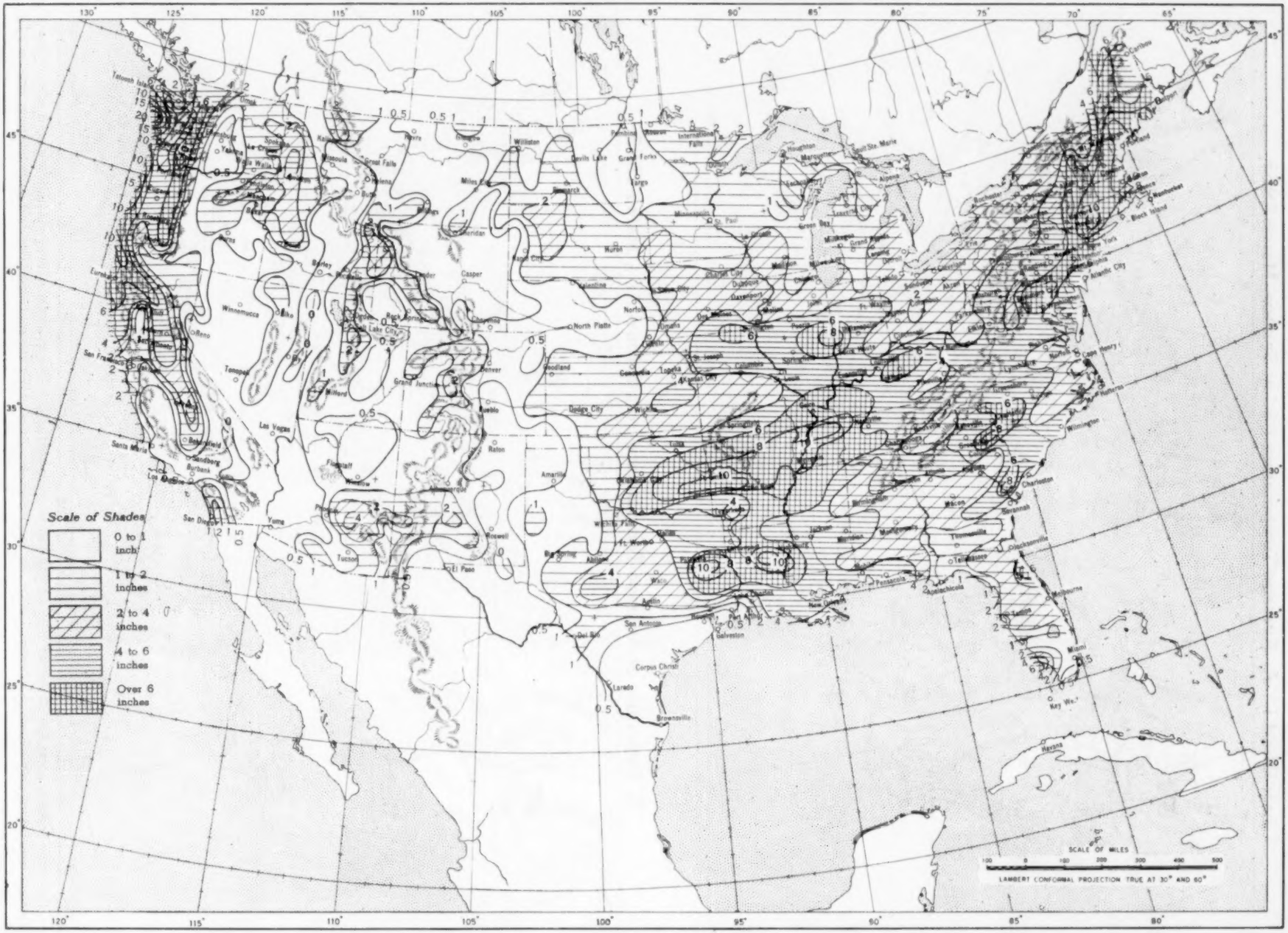


B. Departure of Average Temperature from Normal (°F.), March 1953.



A. Based on reports from 800 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.
B. Normal average monthly temperatures are computed for Weather Bureau stations having at least 10 years of record.

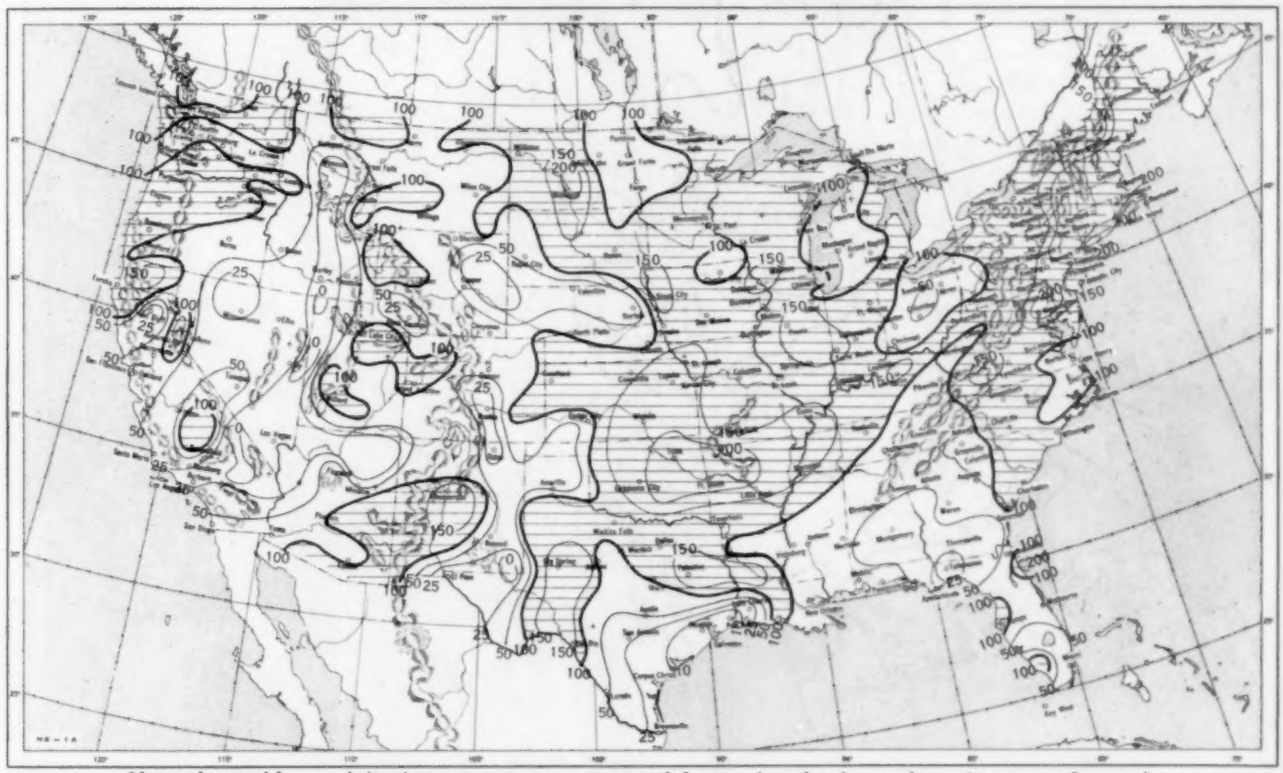
Chart II. Total Precipitation (Inches), March 1953.


Scale of Shades
0 to 1 inch
1 to 2 inches
2 to 4 inches
4 to 6 inches
Over 6 inches
SCALE OF MILES
LAMBERT CONFORMAL PROJECTION TRUE AT 30° AND 60°

Based on daily precipitation records at 800 Weather Bureau and cooperative stations.

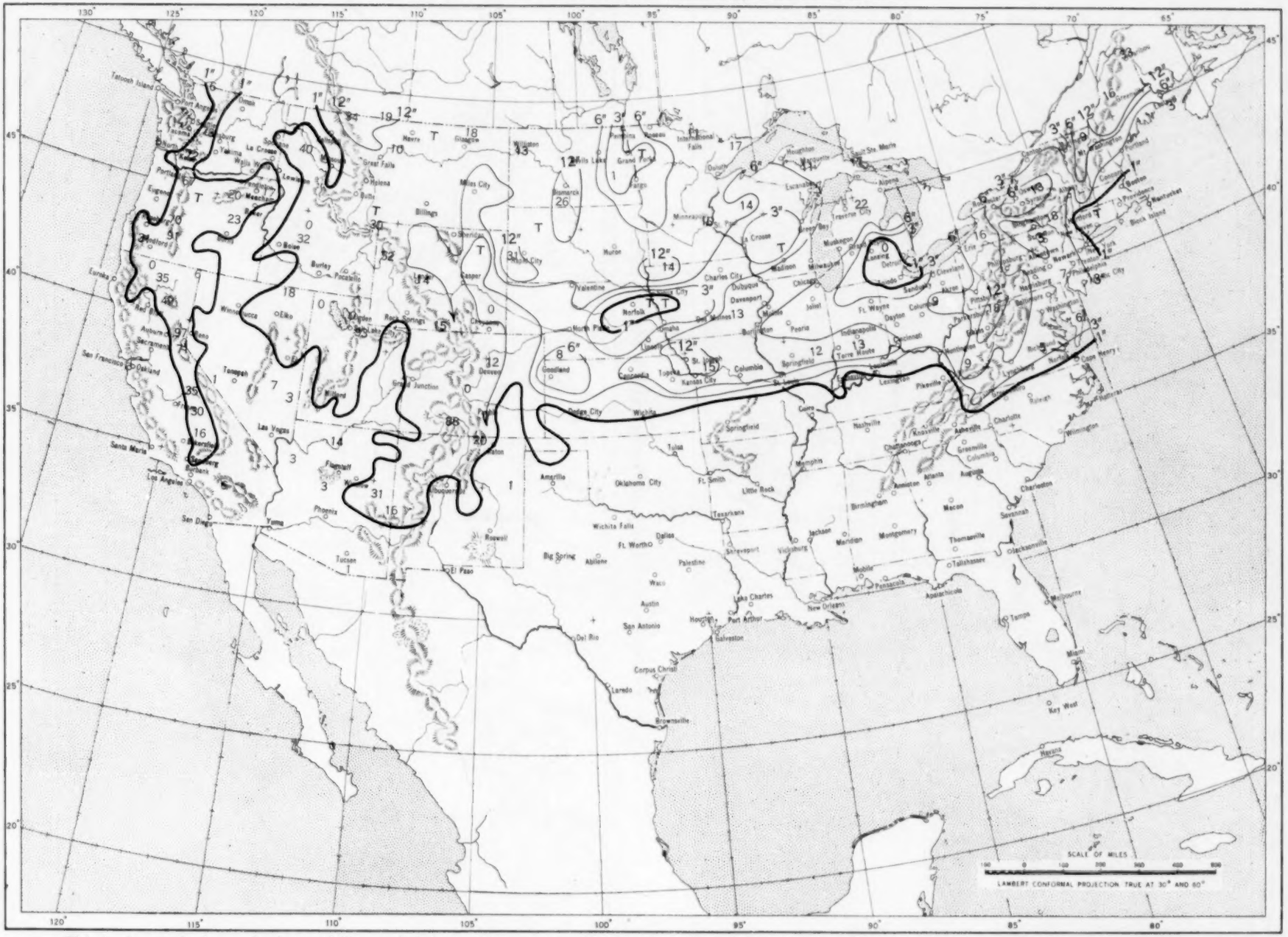
Chart III. A. Departure of Precipitation from Normal (Inches), March 1953.

B. Percentage of Normal Precipitation, March 1953.



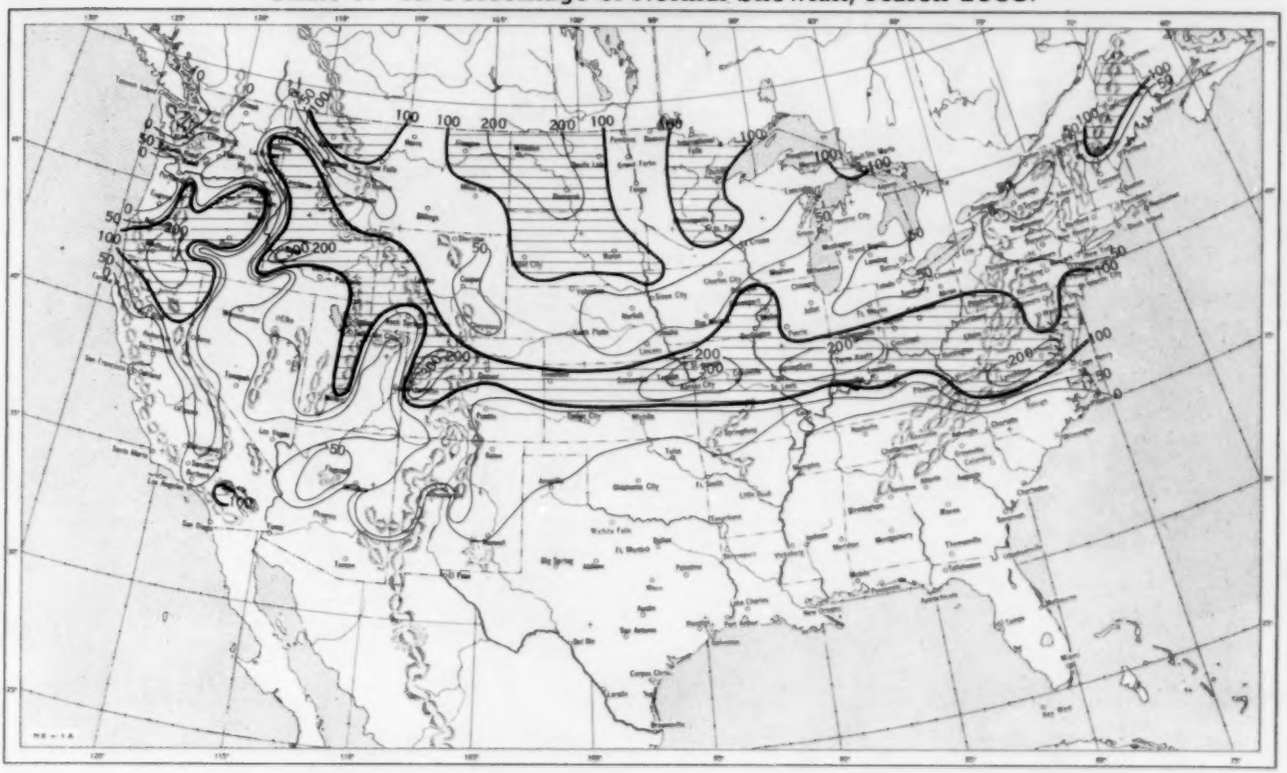
Normal monthly precipitation amounts are computed for stations having at least 10 years of record.

Chart IV. Total Snowfall (Inches), March 1953.

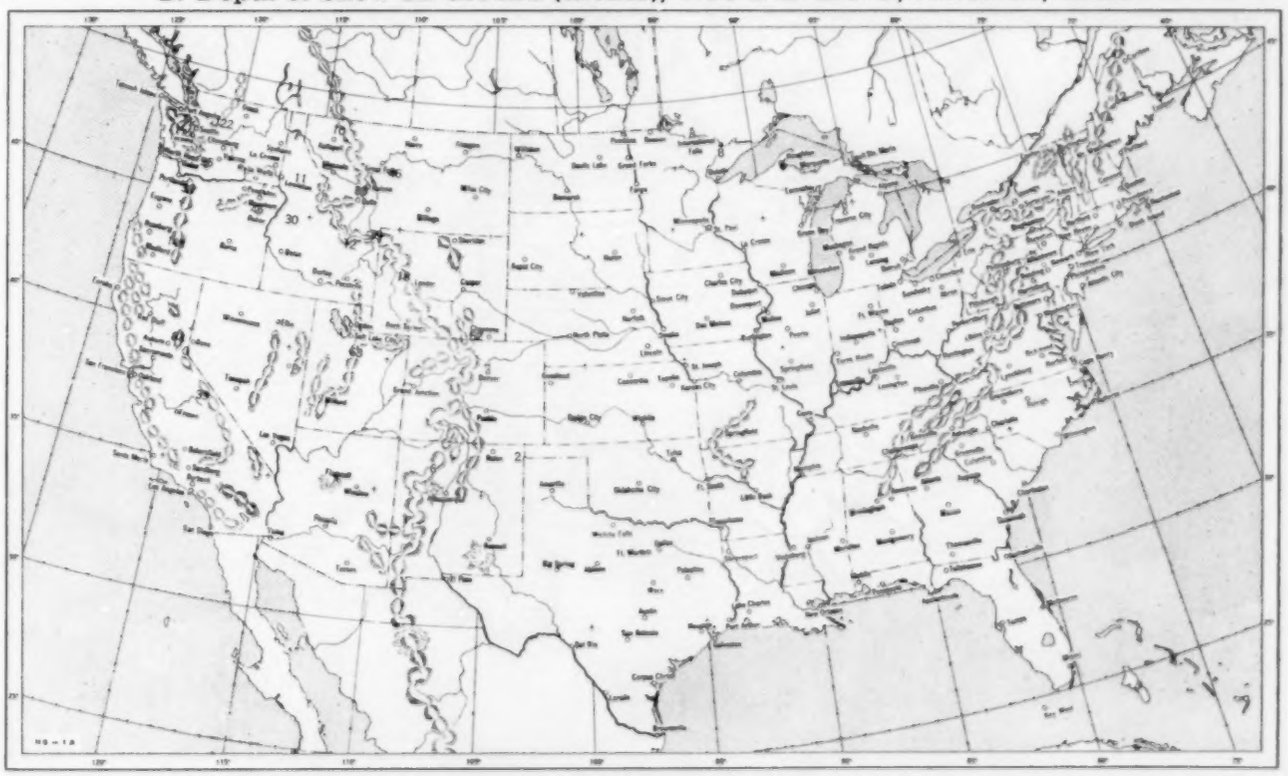


This is the total of unmelted snowfall recorded during the month at Weather Bureau and cooperative stations. This chart and Chart V are published only for the months of November through April although of course there is some snow at higher elevations, particularly in the far West, earlier and later in the year.

Chart V. A. Percentage of Normal Snowfall, March 1953.

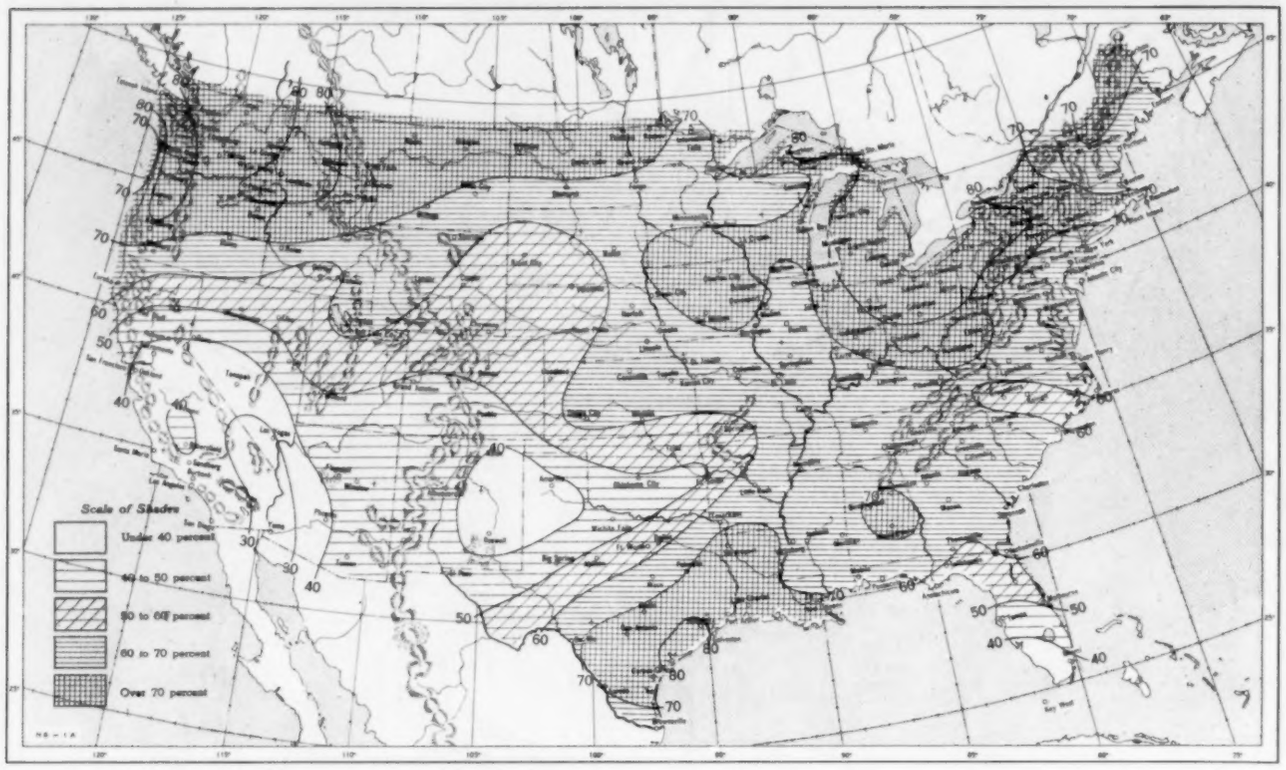


B. Depth of Snow on Ground (Inches), 7:30 a. m. E.S.T., March 31, 1953.

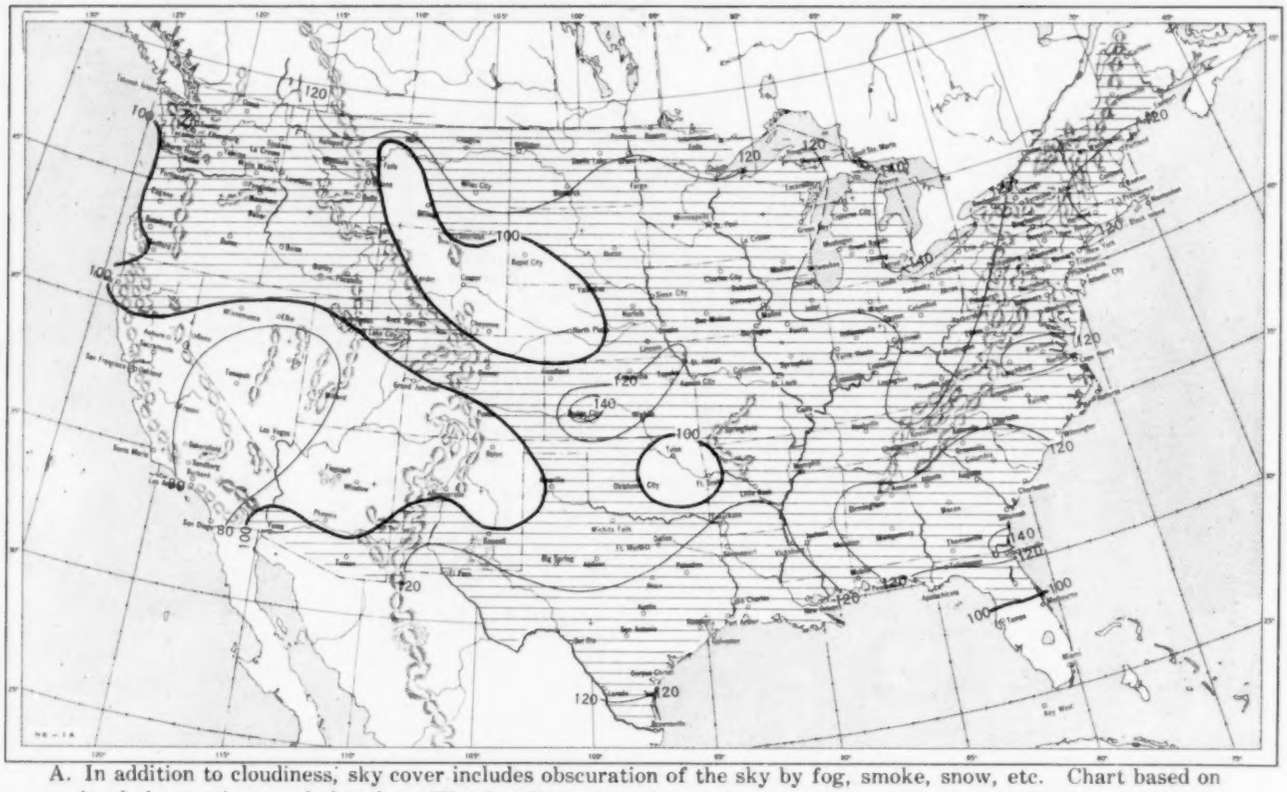


A. Amount of normal monthly snowfall is computed for Weather Bureau stations having at least 10 years of record. B. Shows depth currently on ground at 7:30 a. m. E.S.T., of the Tuesday nearest the end of the month. It is based on reports from Weather Bureau and cooperative stations. Dashed line shows greatest southern extent of snowcover during month.

Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, March 1953.

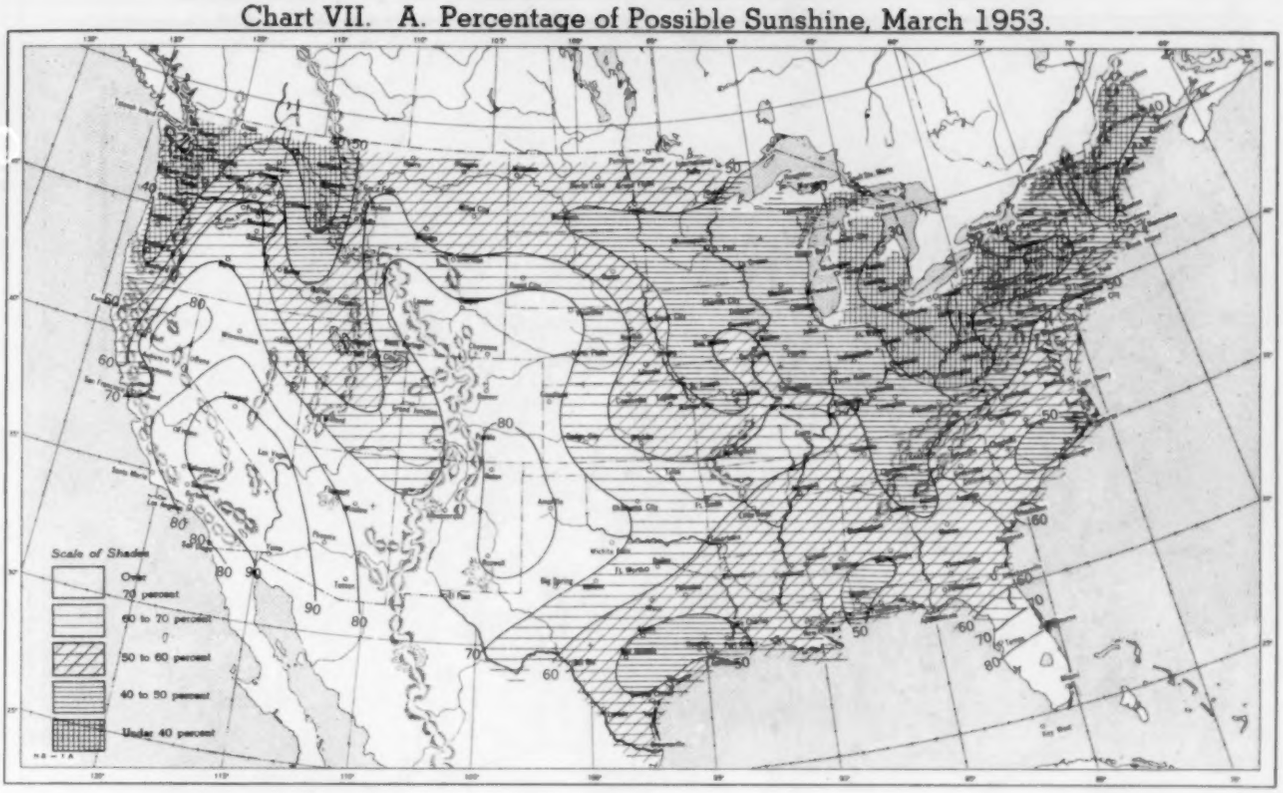


B. Percentage of Normal Sky Cover Between Sunrise and Sunset, March 1953.

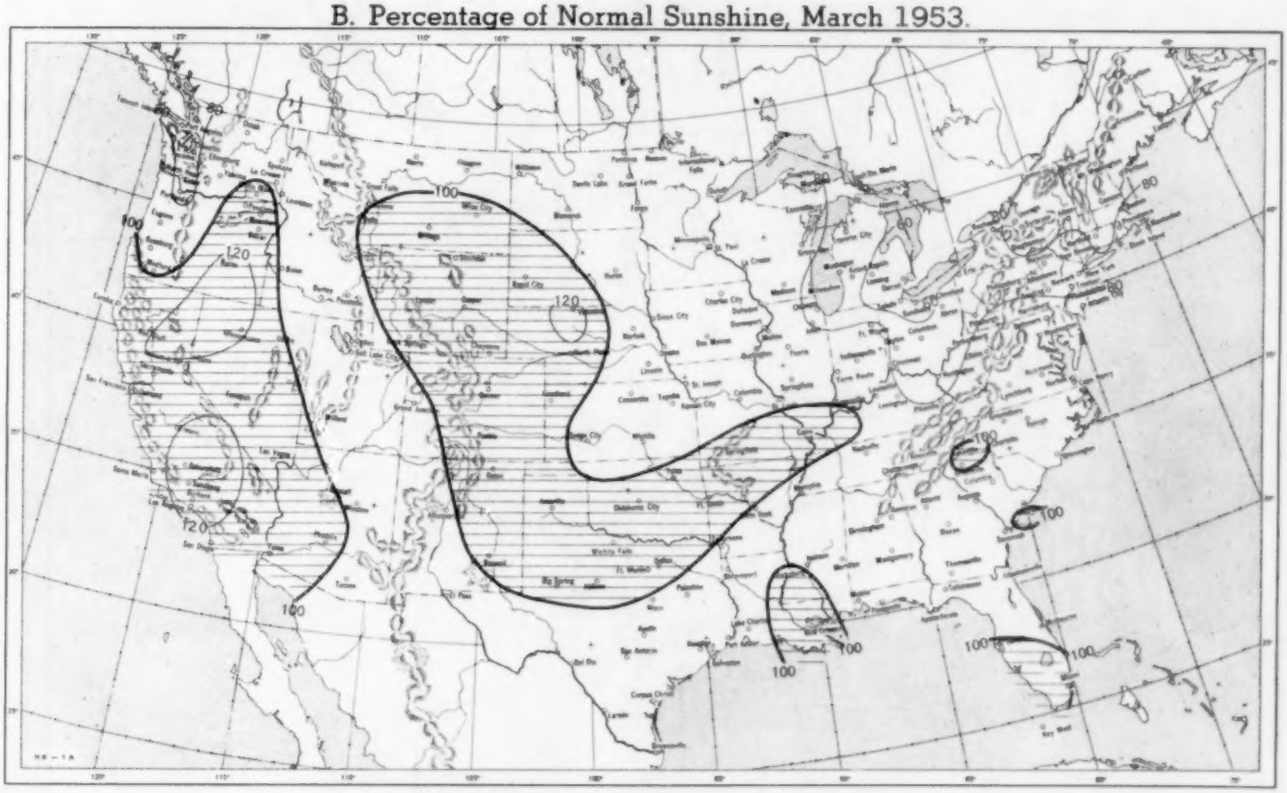


A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII. A. Percentage of Possible Sunshine, March 1953.



B. Percentage of Normal Sunshine, March 1953.



A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, March 1953. Inset: Percentage of Normal

Average Daily Solar Radiation, March 1953.

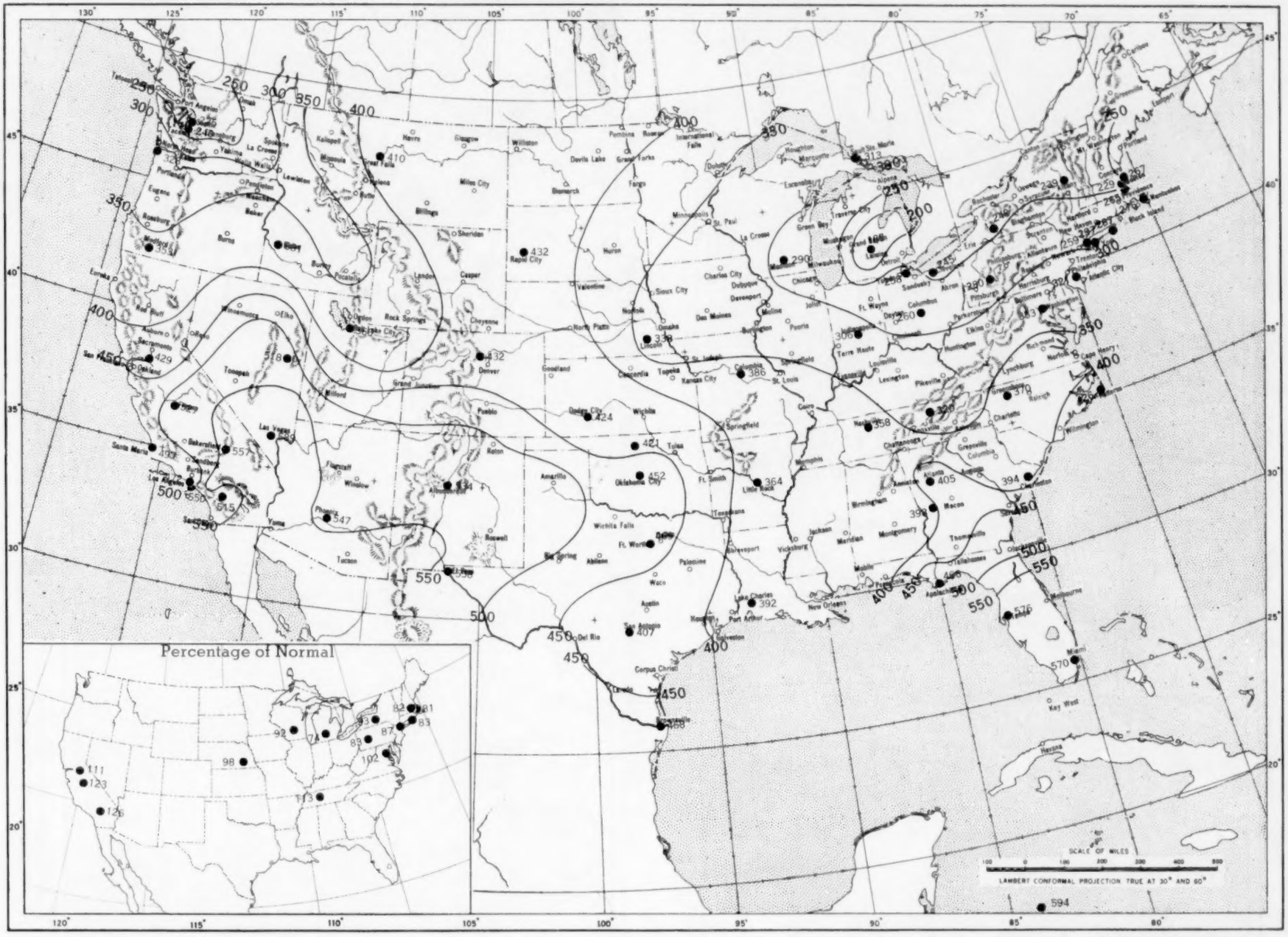
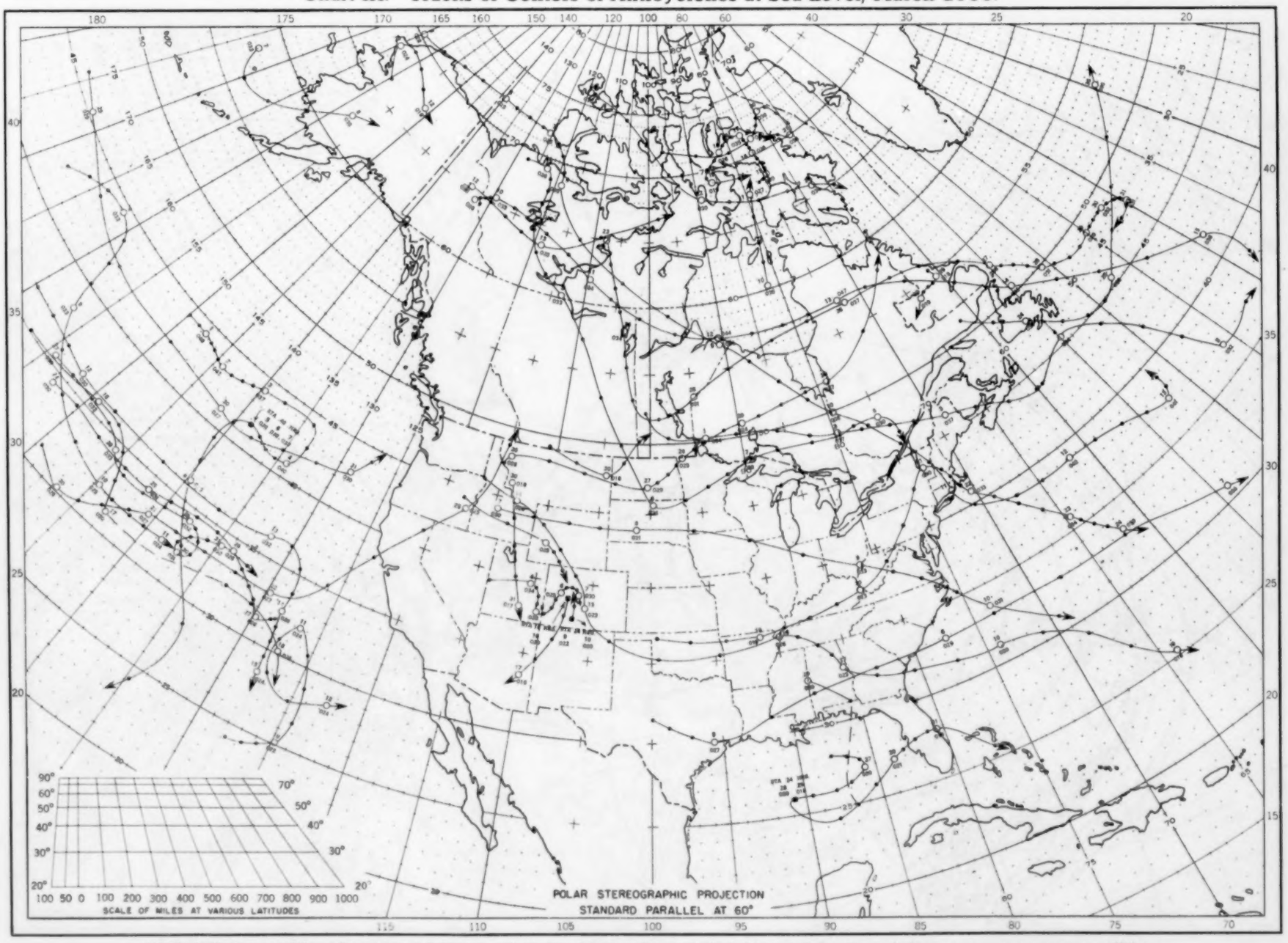


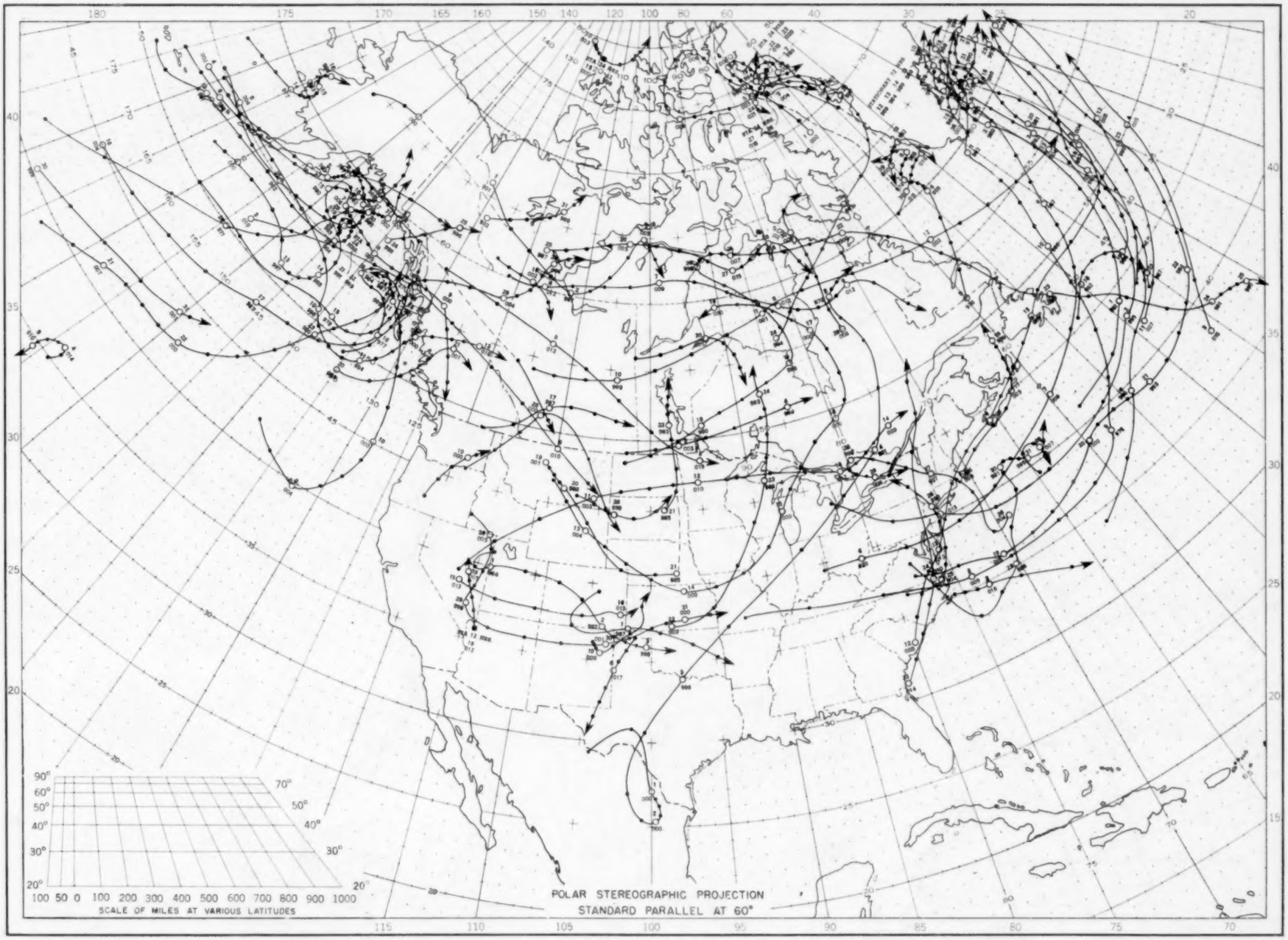
Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm. $^{-2}$). Basic data for isolines are shown on chart. Further estimates are obtained from supplementary data for which limits of accuracy are wider than for those data shown. Normals are computed for stations having at least 9 years of record.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, March 1953.


POLAR STEREOGRAPHIC PROJECTION
STANDARD PARALLEL AT 60°
SCALE OF MILES AT VARIOUS LATITUDES
100 50 0 100 200 300 400 500 600 700 800 900 1000

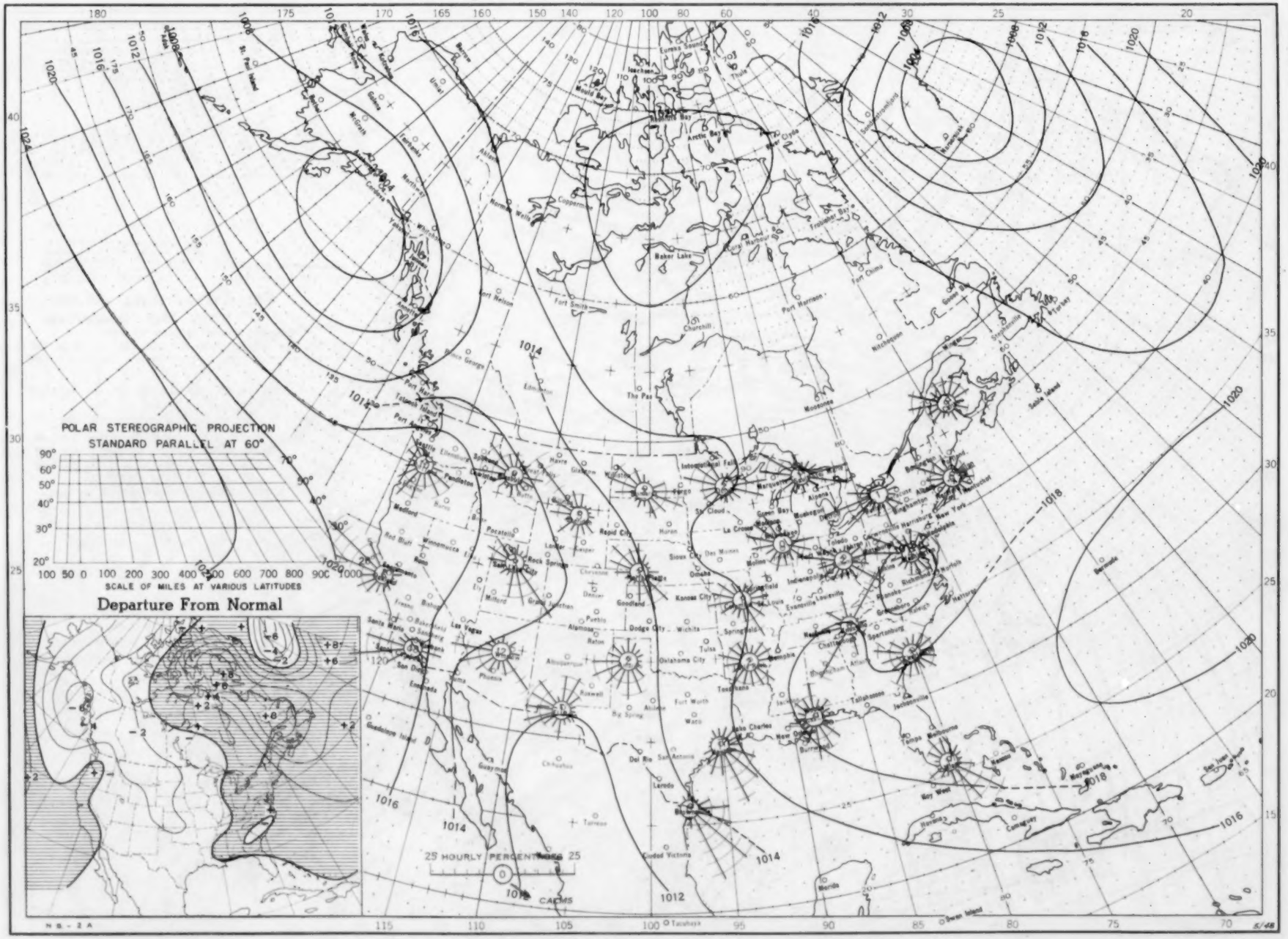
Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, March 1953.


90° 60° 50° 40° 30° 20°
70° 50° 40° 30° 20°
100 50 0 100 200 300 400 500 600 700 800 900 1000
SCALE OF MILES AT VARIOUS LATITUDES
POLAR STEREOGRAPHIC PROJECTION
STANDARD PARALLEL AT 60°

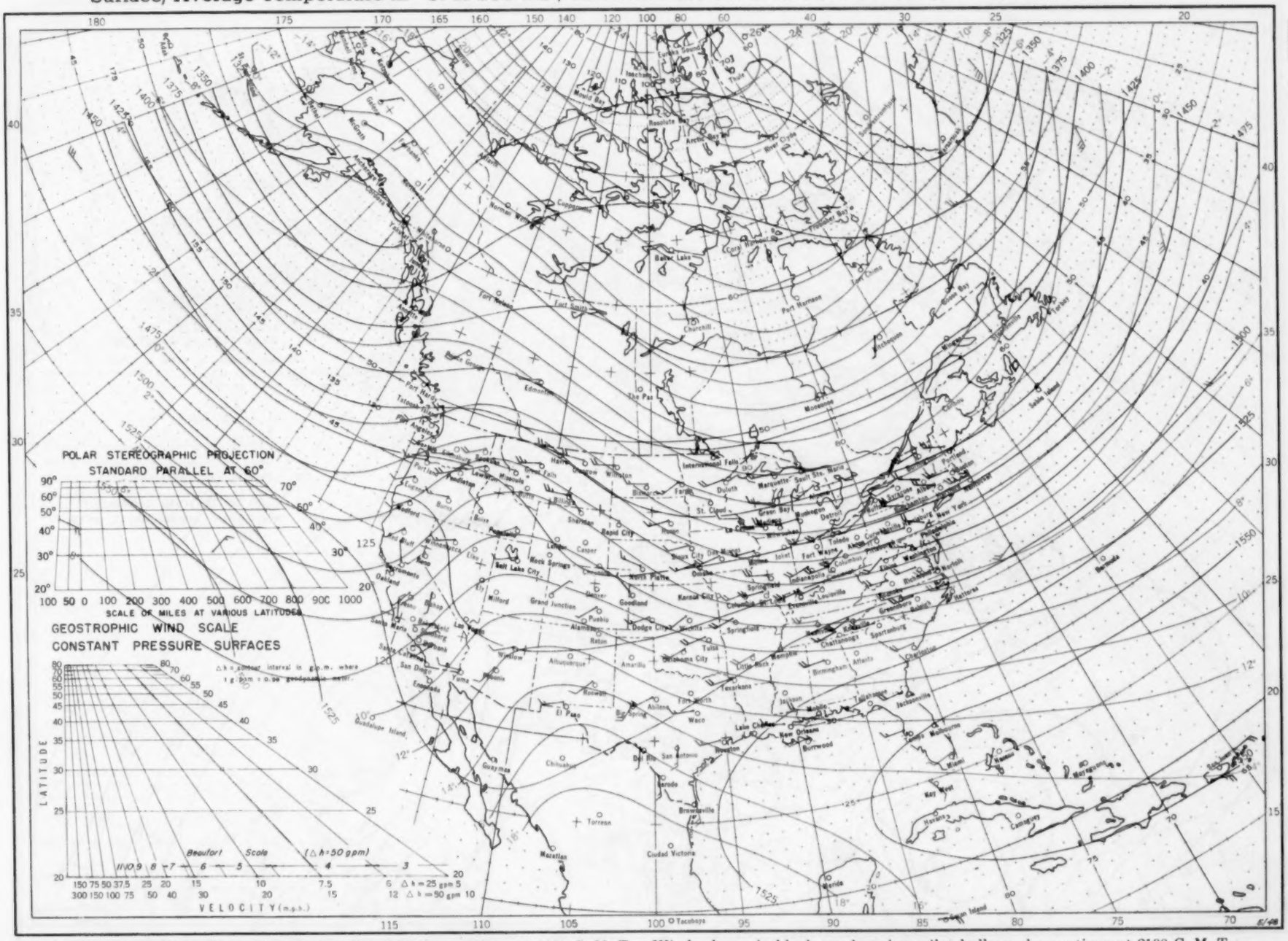
Circle indicates position of center at 7:30 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, March 1953. Inset: Departure of Average Pressure (mb.) from Normal, March 1953.



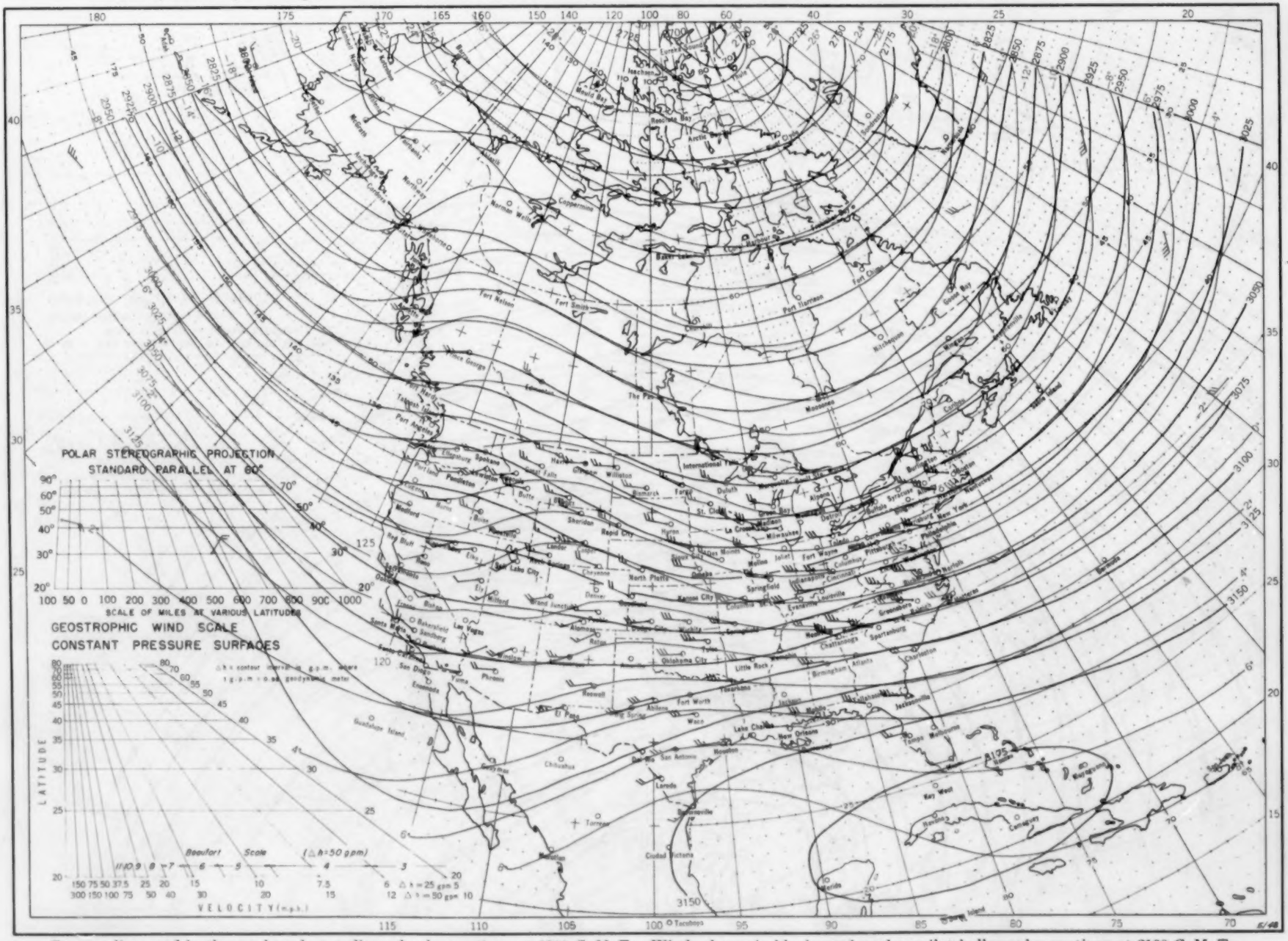
Average sea level pressures are obtained from the averages of the 7:30 a. m. and 7:30 p. m. E. S. T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid based on readings from the Historical Weather Maps (1899-1939) for the 20 years of most complete data coverage prior to 1940.

Chart XII. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 850-mb. Pressure Surface, Average Temperature in °C. at 850 mb., and Resultant Winds at 1500 Meters (m.s.l.), March 1953.



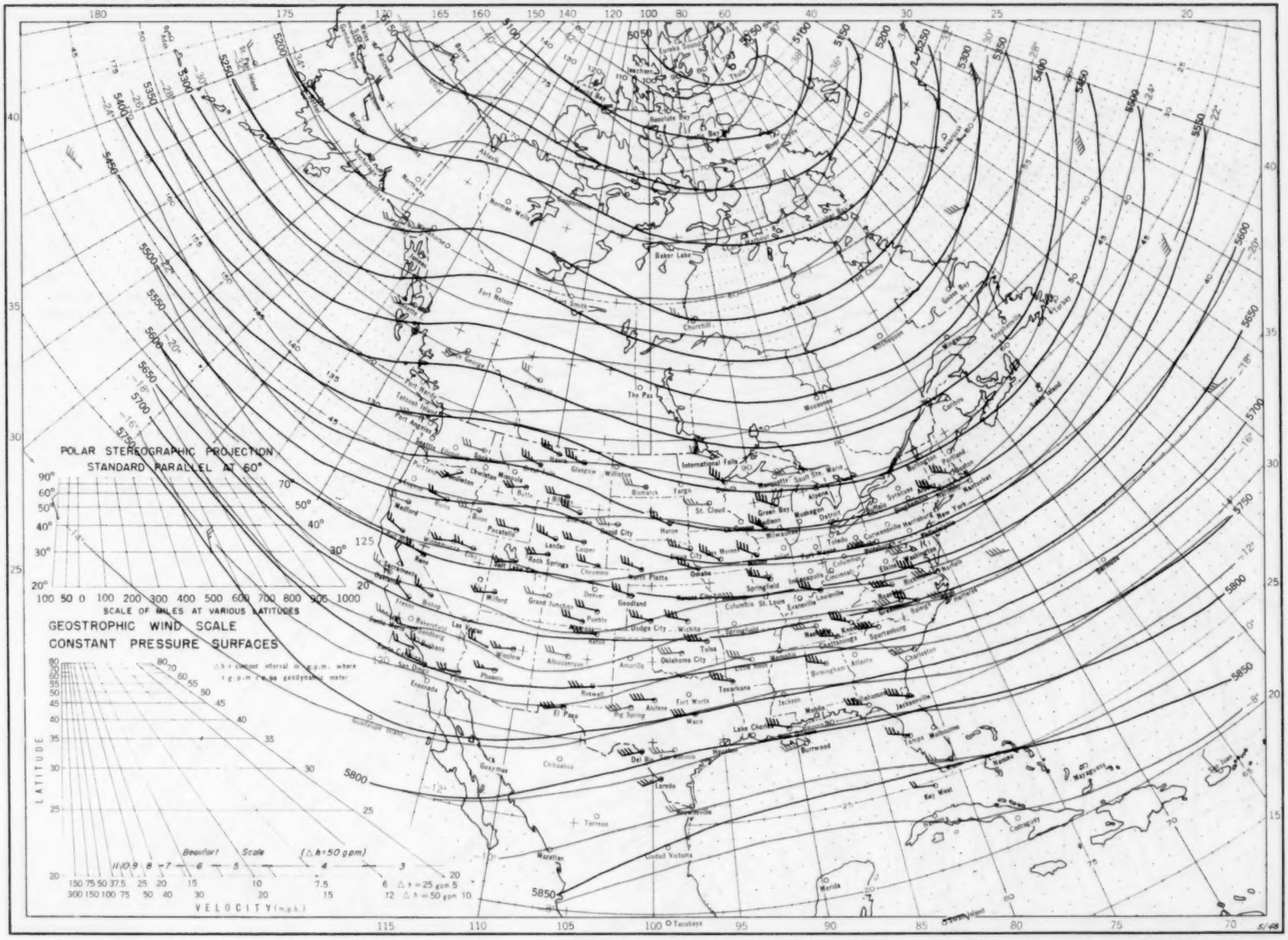
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T.

Chart XIII. Average Dynamic Height in Geopotential Meters (1 g.p.m.. = 0.98 dynamic meters) of the 700-mb. Pressure Surface, Average Temperature in °C. at 700 mb., and Resultant Winds at 3000 Meters (m.s.l.), March 1953.



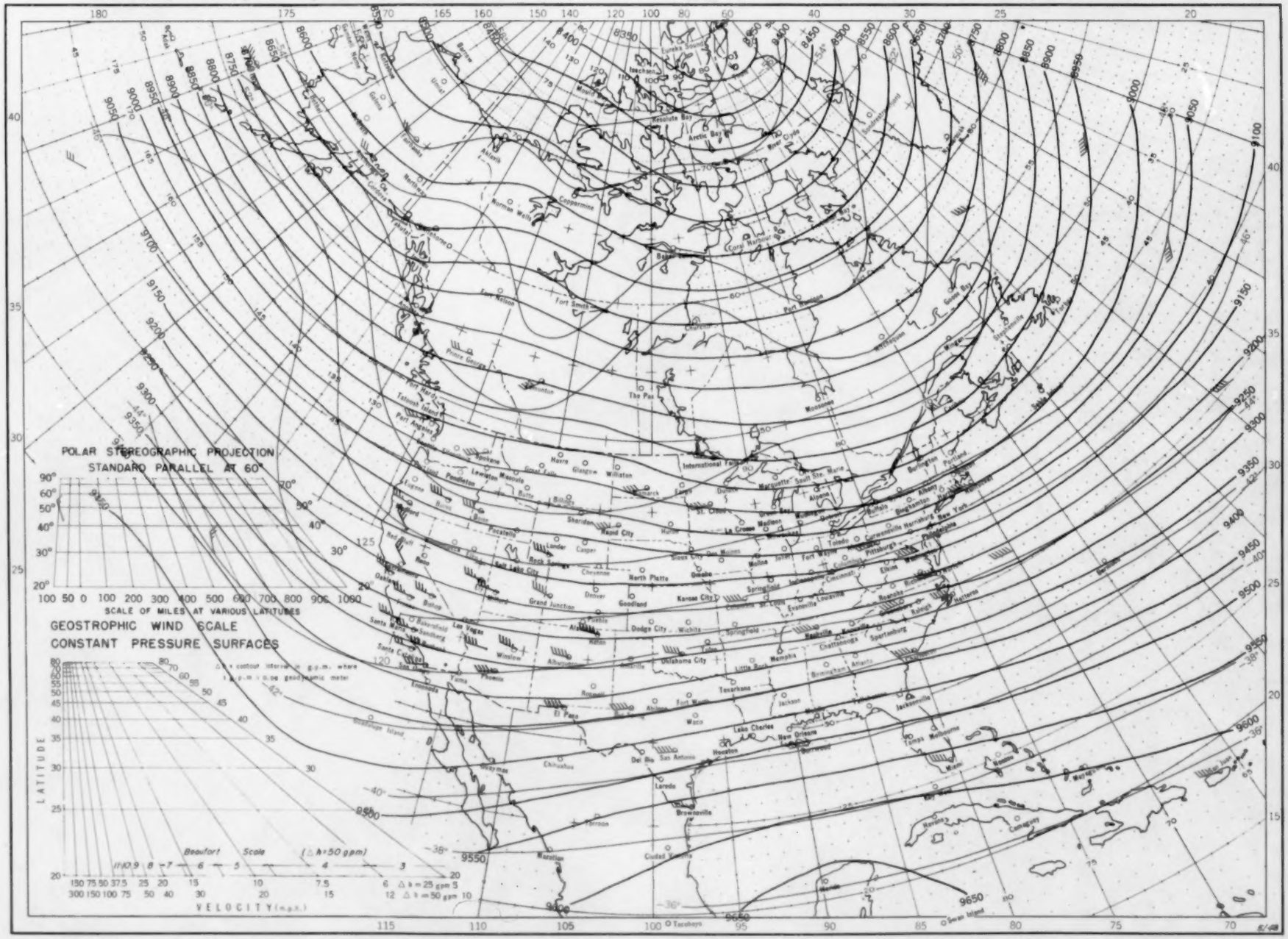
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T.

Chart XIV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 500-mb. Pressure Surface, Average Temperature in °C. at 500 mb., and Resultant Winds at 5000 Meters (m.s.l.), March 1953.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T.

Chart XV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 300-mb. Pressure Surface, Average Temperature in °C. at 300 mb., and Resultant Winds at 10,000 Meters (m.s.l.), March 1953.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T.